WORKSHOP ON THE DEEP CONTINENTAL CRUST OF SOUTH INDIA

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WORKSHOP ON
THE DEEP CONTINENTAL CRUST OF SOUTH INDIA

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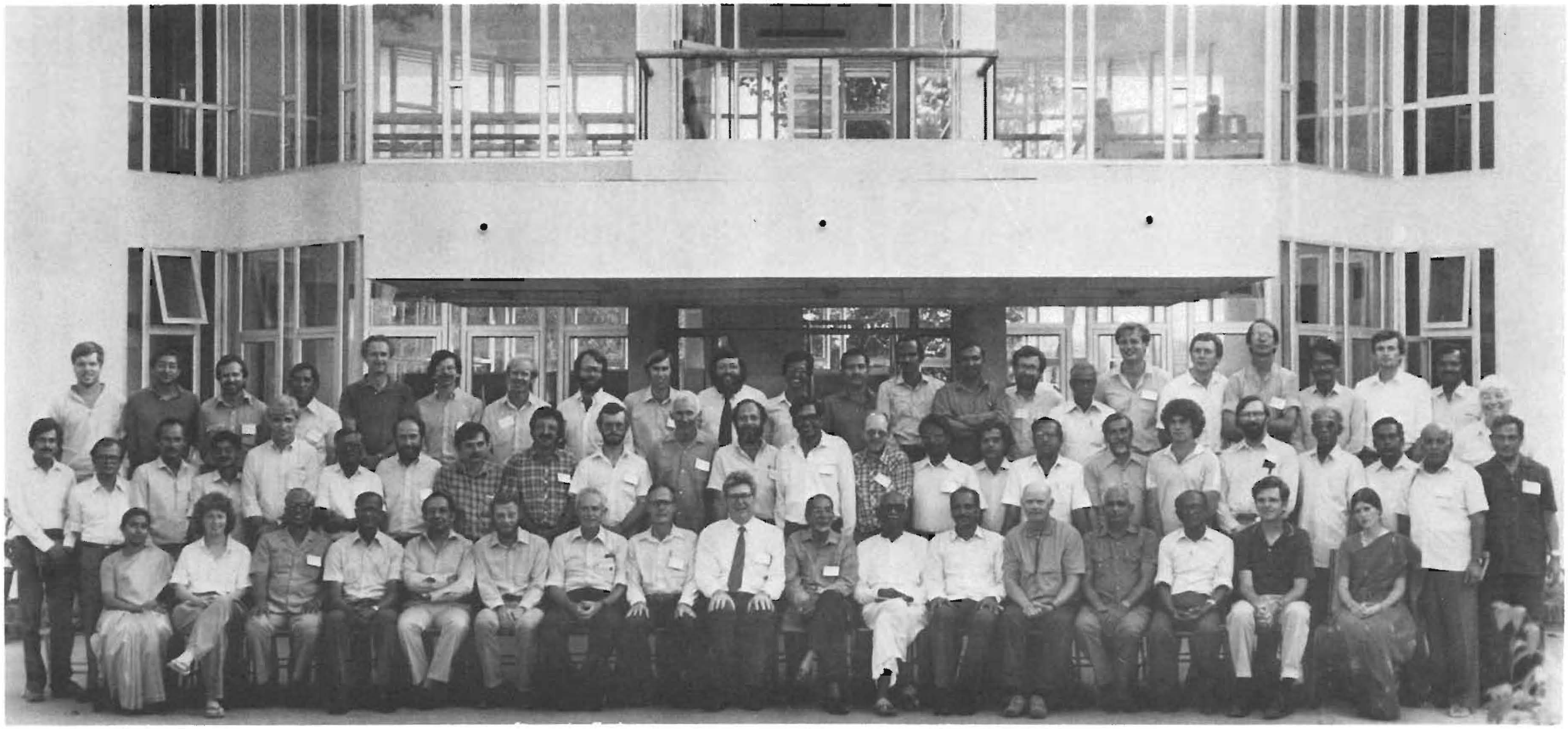
Cover—*Migmatitic Peninsular grandiorite gneiss with patches of brownish charnockite. Kabbal Quarry.* *See p. 304.*



Group Picture—*Participants in the Joint Indo-U.S. Workshop on the Deep Continental Crust of South India. Photo taken January 22, 1988, at the Centre for Earth Science Studies, Trivandrum.*

Introduction

The idea for a Field Workshop in South India originally came from Bob Newton. He and his colleagues had been working in Southern India for several years on problems related to granulite formation, and realized that the time was ripe for an international meeting to discuss the various theories in the field, where we could all examine the spectacular exposures of granulite-in-the-making. Newton first approached Bill Phinney and me with this idea at the 1985 Spring AGU meeting in Baltimore and, with the encouragement of Kevin Burke, we began looking into the possibility of organizing the workshop. The visit of A. S. Janardhan of the University of Mysore to the LPI in the summer of 1985 was timely, and he offered some key suggestions about logistics and support, including the brilliant idea of seeking the help of Dr. B. P. Radhakrishna of the Geological Society of India. During the next year, while Janardhan and Radhakrishna worked out the details from the Indian side, we requested and received funding from the U.S. National Science Foundation and obtained approval from NASA to hold the workshop. Pam Jones and her capable staff in the LPI Projects Office were still recovering from a similar workshop in West Greenland, but were eager for a new adventure, and they began organizing the complex logistics. On January 8, 1988, 35 scientists from the U.S., U.K., Canada, Germany, Greenland, Australia, and Holland met an equal number of Indian scientists in Bangalore, and the workshop began.

During the next two weeks we visited dozens of outcrops and quarries, argued about the superbly exposed features we saw between Bangalore and Trivandrum (over a distance of more than 900 km), and experienced the spectacular scenery, culture, and cuisine of South India. Interspersed with the field excursions were four days of technical sessions, during which we presented and discussed the results of our research. Largely through the organizational efforts of K. V. Krishnamurthy, Director-in-Charge of Operations Karnataka & Goa of the Geological Survey of India, and his staff, the entire workshop operated smoothly and efficiently.

The scientific accomplishments of the workshop are already obvious. Some widely accepted ideas about the origin of granulites, particularly relating to the role of metamorphic fluids, will have to be modified. Many new international collaborative arrangements were initiated. Hundreds of kilograms of samples were collected, and these are likely to provide interesting new data for many years to come.

This volume contains extended abstracts of the papers presented at the technical sessions, summaries of the attendant discussions, up-to-date accounts of the geology of the South Indian Precambrian Shield, and detailed field trip guides to all areas visited. I hope that the report will serve as a convenient source of information and reference to all those interested in one of the classic Precambrian high-grade terranes on Earth.

Lewis D. Ashwal
Houston, Texas
April, 1988

Program

January 9th—Institution of Engineers, Bangalore

8:30 a.m.

Introduction to the Workshop
Chairman: Kurien Jacob

Welcome address: Dr. Kurien Jacob, President, Geological Society of India
Inauguration of the Workshop: Sri. D. P. Dhoundial, Director General, Geological Survey of India
Objectives of the Workshop: Dr. Kevin Burke, Director, Lunar and Planetary Institute
Vote of Thanks

11:00 a.m.

The Kolar Schist Belt and Other Supracrustal Rocks
Chairmen: G. N. Hanson and V. Rajamani
Summarizer: E. J. Krogstad

Rajamani V.*
Introduction to the Kolar Schist Belt

Mukhopahyay D. K.*
Structural Evolution of the Kolar Schist Belt, South India

Balakrishnan S.* Hanson G. N. Rajamani V.
Geochemistry of Amphibolites from the Kolar Schist Belt

Siva Siddaiah N.* Rajamani V.
Geochemistry and Origin of Gold Mineralization in the Kolar Schist Belt

Krogstad E. J.* Hanson G. N. Rajamani V.
U-Pb Ages and Sr, Pb and Nd Isotope Data for Gneisses near the Kolar Schist Belt: Evidence for the Juxtaposition of Discrete Archean Terranes

Hanson G. N.* Krogstad E. J. Rajamani V.
Tectonic Setting of the Kolar Schist Belt, Karnataka, India

2:00 p.m.

Melting and Thermal Relations in the Deep Crust
Chairmen: K. Burke and M. Gupta
Summarizer: P. Morgan

Devaraju T. C.* Laajoki K. Wodeyar B. K.
Metasediments of the Deep Crustal Section of Southern Karnataka

Arculus R. J.*
Crustal Growth—Some Major Problems

Haggerty S. E.* Toft P. B.
Petrochemical and Petrophysical Characterization of the Lower Crust and the Moho Beneath the West African Craton, Based on Xenoliths from Kimberlites

Burke K.*
How Widely is the Andean Type of Continental Margin Represented in the Archean?

Santosh M.* Drury S. A. Iyer S. S.
Pan-African Alkali Granites and Syenites of Kerala as Imprints of Taphrogenic Magmatism in the South Indian Shield

Barker F.* Arth J. G.
Nature of the Coast Batholith, Southeastern Alaska: Are There Archaean Analogs?

Morgan P.* Ashwal L.
Heat Transfer by Fluids in Granulite Metamorphism

*Designates speaker

January 13—Department of Geology, University of Mysore

8:30 a.m.

Fluids in High Grade Metamorphism—I
Chairmen: J. Touret and S. K. Sen
Summarizer: R. Newton

Newton R. C.*
Nature and Origin of Fluids in Granulite Facies Metamorphism

Valley J. W.*
Granulites: Melts and Fluids in the Deep Crust

Wickham S. M.*
Underplating, Anatexis and Assimilation of Metacarbonate; A Possible Source for Large CO_2 Fluxes in the Deep Crust

Chacko T.* Ravindra Kumar G. R. Peterson J. W.
Water Activities in the Kerala Khondalite Belt

Hansen E.* Hunt W. Jacob S. C. Morden K. Reddi R. Tacy P.
Evidence for CO_2-rich Fluids in Rocks from the "Type" Charnockite Area near Pallavaram, Tamil Nadu

Henry D. J.*
Cl-rich Minerals in Archean Granulite Facies Ironstones from the Beartooth Mountains, Montana, USA: Implications for Fluids Involved in Granulite Metamorphism

Hollister L. S.*
CO_2-rich Fluid Inclusions in Greenschists, Migmatites, Granulites, and Hydrated Granulites

2:00 p.m.

Fluids in High Grade Metamorphism—II
Chairmen: S. K. Sen and J. Touret
Summarizer: R. Newton

Waters D.*
Dehydration Melting and Formation of Granulite Facies Assemblages

Santosh M.* Jackson D. H. Mattey D. P. Harris N. B. W.
Characteristics and Carbon Stable Isotopes of Fluids in the Southern Kerala Granulites and Their Bearing on the Source of CO_2

Sisson V. B.* Leeman W. P.
The Role of Boron and Fluids in High Temperature, Shallow Level Metamorphism of the Chugach Metamorphic Complex, Alaska

Morrison J.* Valley J. W.
Post-Metamorphic Fluid Infiltration into Granulites from the Adirondack Mts., USA

Klatt E. Hoernes S. Raith M.*
Characterization of Fluids Involved in the Gneiss-Charnockite Transformation in Southern Kerala (India)

Srikantappa C.* Ashamanjari K. G. Prakesh Narasimha K. N. Raith M.
Retrograde, Charnockite-Gneiss Relations in Southern India

Touret J. L. R.
Nature and Interpretation of Fluid Inclusions in Granulites

January 19—Centre for Earth Science Studies, Trivandrum

8:30 a.m.

Metamorphic Petrology and Tectonics
Chairmen: N. Raith and K. Naha
Summarizers: J. Percival and K. Burke

Mezger K.* Bohlen S. R. Hanson G. N.
P-T-t Path for the Archean Pikwitonei Granulite Domain and Cross Lake Subprovince, Manitoba, Canada

Raith M.* Hengst C. Nagel B. Bhattacharya A. Srikantappa C.
Metamorphic Conditions in the Nilgiri Granulite Terrane and the Adjacent Moyar and Bhavani Shear Zones: A Reevaluation

Ravindra Kumar G. R.* Chacko T.
Petrology and Tectonic Development of Supracrustal Sequence of Kerala Khondalite Belt, Southern India

Kusky T. M.*
Accretion of the Archean Slave Province

Kidd W. S. F.* Kusky T. M. Bradley D. C.
Late Archean Greenstone Tectonics—Evidence for Thermal and Thrust-Loading Lithospheric Subsidence from Stratigraphic Sections in the Slave Province, Canada

Friend C. R. L. Nutman A. P. McGregor V. R.*
Significance of the Late Archaean Granulite Facies Terrain Boundaries, Southern West Greenland

Percival J. A.*
Accretionary Origin for the Late Archean Ashuanipi Complex of Canada

1:30 p.m.

Granulite Terrains: Characteristics and Transitions
Chairmen: K. Naha and N. Raith
Summarizer: J. Morrison

Raith M.* Klatt E. Spiering B. Srikantappa C. Stähle H. J.
Gneiss-Charnockite Transformation at Kottavattam, Southern Kerala (India)

Raith M.* Stähle H. J. Hoernes S.
Kabbaldurga-type Charnockitization: A Local Phenomenon in the Granulite to Amphibolite Grade Transition Zone

Anantha Iyer G. V.*
Gneiss-Charnockite-Granite Connection in the Archaean Crust of Karnataka Craton, India

Sharma R. S.*
Granulites from Northwest Indian Shield: Their Differences and Similarities with Southern Indian Granulite Terrain

Myers J. S.*
Tectonic Evolution of the Western Australian Shield

January 22—Centre for Earth Science Studies, Trivandrum

8:30 a.m.

Anorthosites and Related Rocks
Chairmen: A. S. Janardhan and W. C. Phinney
Summarizer: D. J. Henry

Ashwal L. D.*
Anorthosites: Classification, Mythology, Trivia, and a Simple Unified Theory

Leelanandam C.* Ratnakar J. Narsimha Reddy M.
Anorthosites and Alkaline Rocks from the Deep Crust of Peninsular India

Wiebe R. A.* Janardhan A. S.
Metamorphism of the Oddañchatram Anorthosite, Tamil Nadu, South India

McLelland J.*
U-Pb Zircon Geochronology and Evolution of Some Adirondack Meta-Igneous Rocks

Frost B. R.* Frost C. D.
Significance of Elevated K/Rb Ratios in Lower Crustal Rocks

Phinney W. C.* Morrison D. A. Maczuga D. E.
Tectonic Implications of Anorthosite Occurrences

Morrison D. A.* Phinney W. C. Maczuga D. E.
Petrogenetic Significance of Plagioclase Megacrysts in Archean Rocks

Sugavanam E. B.* Vidyadharan K. T.
Structural Patterns in High Grade Terrain in Parts of Tamil Nadu and Karnataka

1:30 p.m.

Tectonics and Ages of Deep Crust
Chairmen: K. Gopalan and P. Taylor
Summarizer: L. D. Ashwal

Ramakrishnan M.*
Tectonic Evolution of the Archaean High-Grade Terrain of Southern India

Naha K.*
Structural Relations of Charnockites of South India

Mishra D. C.*
Geophysical Evidences for a Thick Crust South of Palghat-Tiruchi Gap in the High Grade Terrains of South India

Moorbath S. Taylor P. N.*
Early Precambrian Crustal Evolution in Eastern India: The Ages of the Singhbhum Granite and Included Remnants of Older Gneiss

Taylor P. N.* Chadwick B. Friend C. R. L. Ramakrishnan M. Moorbath S. Viswanatha M. N.
New Age Data on the Geological Evolution of Southern India

Gopalan K. Srinivasan R.*
Present Status of the Geochronology of the Early Precambrian of South India

SUMMARIES OF TECHNICAL SESSIONS

The Kolar Schist Belt and Other Supracrustal Rocks

E. J. Krogstad

V. Rajamani introduced the Kolar Schist Belt and summarized the talks to follow about specific aspects of the Belt and surrounding terranes. The talk provided an overview of the various lithologies within the Belt and in the surrounding gneisses. The amphibolite-dominated schist belt includes at least four "packages" of metatholeiites and metakomatiites distinct in major and trace element characteristics. Those amphibolites of the west side of the schist belt resemble what may have been the Archean equivalent of mid-ocean ridge basalt (MORB); those on the east side were, by contrast, derived from a LREE-enriched source, like those of present-day ocean island basalts (OIB) or island arc volcanics. Gneisses of largely granodioritic composition surround the schist belt and are broadly similar in composition, although they are of various ages and are derived from different sources. Rajamani presented the model of the JNU-Stony Brook group, which is that the Kolar Schist Belt is the site of a late Archean or earliest Proterozoic suture zone.

In discussion, Rajamani was asked by K. Burke to explain how the REE data from the Kolar amphibolites could be used to relate them to modern MORBs. Rajamani responded by saying that some of the Kolar amphibolites are depleted in LREE, as are present-day MORBs, but some are LREE-enriched, like present-day OIBs.

D. K. Mukhopadhyay spoke next on the structural evolution of the Kolar Schist Belt. He described his evidence from structures in the ferrigenous quartzite within the schist belt for two periods of nearly coaxial isoclinal folding attributable to E-W compression. This folding was followed by collapse of the F_1/F_2 folds, forming open F_3 folds with NNE-SSW axes. Finally, a period of N-S shortening caused a broad warping of the earlier N-S trending fold axes. There is evidence within the gneisses for shearing produced by similar, nearly E-W compression.

Mukhopadhyay was asked by J. McLelland whether there were any stretching lineations produced by the deformation in the KSB area. Mukhopadhyay responded by stating that stretching lineations were produced both by the F_1 and F_2 folding episodes. McLelland then asked whether there is any evidence for the formations of sheath folds in the area. Mukhopadhyay stated that protosheaths were not well developed because of insufficient deformation. G. V. Anantha Iyer asked whether changes in elemental abundances resulted from the deformation. Mukhopadhyay responded by saying that there is no evidence for this in the Kolar Schist Belt. K. Gopalan inquired about the timing of the compression of the Kolar area. Mukhopadhyay suggested that the timing of compression may be that represented by the 2420 Ma $^{40}Ar/^{39}Ar$ age of muscovite of Krogstad et al. (this session). K. Naha asked if the F_1 and F_2 structures are nearly parallel where both are seen. Mukhopadhyay asked if there is any evidence to indicate whether F_1 and F_2 fold axes are parallel, perpendicular, or oblique to the direction of maximum elongation. Mukhopadhyay responded by stating that there are presently insufficient data to make this distinction.

S. Balakrishnan spoke next on the geochemistry of amphibolites from the Kolar Schist Belt. He described how the Nd isotope data suggest that the amphibolites from the schist belt were derived from long-term depleted mantle sources at about 2.7 Ga (ϵ_{Nd} ranging from +2 to +8). Trace element and Pb isotope data from the amphibolites also suggest that the sources for the amphibolites on the western and eastern sides of the narrow schist belt were derived from different sources. The Pb data from one outcrop of the central tholeiitic amphibolites lie on a 2.7-Ga isochron with a low model μ_1. The other amphibolites (W komatiitic, E komatiitic, and E tholeiitic) do not define isochrons, but suggest that they were derived from sources with distinct histories of U/Pb. There is some suggestion that the E komatiitic amphibolites may have been contaminated by fluids carrying Pb from a long-term, high U/Pb source, such as the old granitic crust on the west side of the schist belt. This is consistent with published galena Pb isotope data from the ore lodes within the belt, which also show a history of long-term U/Pb enrichment.

R. Arculus suggested that the high values of ϵ_{Nd} reported by Balakrishnan are without parallel in the literature for Archean rocks. Balakrishnan responded by saying that these values have been reproduced, and that they represent a long-term LREE-depleted mantle source by 2.7 Ga. The question of effects by metamorphism in the Kolar area on the various isotopic systems was raised by Gopalan. Balakrishnan suggested that the Pb data indicate mobility of Pb, and possibly U, but there is no evidence for alteration of the Sm-Nd *systematics. R. Srinivasan asked whether the classification of the various amphibolites was based solely on chemical analyses. Balakrishnan observed that the distinction between the various units was made from field as well as laboratory data. Gopalan asked why no attempt has been made to utilize the Rb-Sr system in the study of the Kolar amphibolites. Balakrishnan reminded the audience that Rb-Sr systematics in Munro Township komatiites have been disturbed, although these rocks had been subjected to lower metamorphic grades and strain. P. Taylor asked Balakrishnan about the model μ_1 values of the amphibolites. It was stated that for the suite in which the Pb systematics seemed relatively undisturbed (W tholeiitic amphibolites) the model μ_1 was about 7.5. M. Ramakrishnan commented that one should be careful about classification of amphibolites as metamorphosed komatiites and tholeiites when all primary textures have been destroyed by recrystallization.*

N. Siva Siddaiah then presented evidence for two discrete types of gold mineralization in the Kolar Schist Belt. Siva Siddaiah suggested that the mineralization in the sulfide lodes in the western part of the schist belt was probably the result of a volcanic exhalative process. The higher grade Au mineralization in the Au-quartz lodes in the eastern part of the belt may be due to hydrothermal alteration accompanying emplacement of the Champion Gneiss and during subsequent shearing.

R. C. Newton asked Siva Siddaiah whether the recent model of E. M. Cameron (leaching of Au by oxidizing, CO_2-rich solutions from the lower crust and deposition of the Au in the sulfide-rich upper crust in quartz-carbonate veins) could apply to the Au mineralization in the Kolar Schist Belt. Siva Siddaiah allowed that possibility, but suggested that determination of such a process was beyond the scope of the present study. M. Santosh suggested that the presence of CO_2-rich fluid inclusions in the Kolar Au-quartz lodes was permissive evidence for such a process having operated. Gopalan asked if the mineralization at Kolar occurred at 2.7 Ga. Rajamani responded by stating that there is evidence for several periods of mineralization. M. Mukherjee made several objections to Siva Siddaiah's generalizations, but there was no further discussion on these points.

Uranium-lead ages and Sr, Pb, and Nd isotopic data for gneisses near the Kolar Schist Belt and their interpretation as evidence for the juxtaposition of discrete Archean terranes were presented next by E. J. Krogstad. The granodioritic Kambha gneiss east of the schist belt has a zircon age of 2532 ± 3 Ma and mantle-like initial Sr, Pb, and Nd isotopic ratios. Therefore these gneisses are thought to represent new crust added to the craton in the latest Archean. By contrast, more mafic Dod gneisses and leucocratic Dosa gneisses west of the schist belt (2632 ± 7 and 2610 ± 10 Ma) show evidence for contamination of their magmatic precursors (LREE-enriched mantle-derived for the Dod gneisses) by older (>3.2 Ga) continental crust. Fragments of this older crust may be present as granitic and tonalitic inclusions in the 2.6-Ga gneisses and in shear zones. The antiquity of these fragments is supported by their Nd, Sr, and Pb isotopic compositions and by 2.8- to >3.2-Ga zircon cores.

Arculus asked if the chemistry of the Dod gneiss may not have resulted from a mixture of mantle-derived and crust-derived materials, rather than from enriched mantle sources. Krogstad replied that although there is evidence for contamination of the magmatic precursors of the Dod gneiss by crustal materials, the Nd vs. Sm/Nd correlation of the Dod gneiss requires that the enrichment of LREEs in the mantle-derived, more primitive Dod gneiss magmatic precursors was equivalent to that of the crustal contaminant. D. C. Mishra asked if the Kolar Schist Belt has an evolutionary history different from those of the schist belts in the western part of the craton. Krogstad replied that the suture model proposed for Kolar should not be applied to other schist belts without evidence to suggest similar histories of these belts. Burke asked why the model should not be extended to the west. Krogstad replied that since the structural grain of the craton is dominantly N-S, the most likely directions to extend the Kolar model are N-S, and that the western schist belts may be entirely different in ages and histories. Burke commented that the model proposed from the Kolar studies is not new, but the study was perhaps the first detailed geochemical analysis of a proposed Archean suture. He added that the structural complexities of Archean greenstone belts may suggest that only through studies utilizing geochemical, isotopic, and age characterizations of greenstone belts and adjacent rocks can their tectonic histories be reconstructed.

G. N. Hanson presented the last talk of the Kolar part of the session, which was on the tectonic setting of the Kolar Schist Belt and why the belt may represent a late Archean suture. Hanson summed up the isotopic and chronological evidence that suggest diverse origins of the various "packages" of supracrustal rocks within the schist belt and the two gneiss terranes adjoining the belt. The eastern and western amphibolites were derived from sources at similar depths in the mantle (probably at similar ages, ca. 2.7 Ga), but these sources had distinct trace element compositions and histories. A distinctive feature of these differences was shown by the differences between the east and west amphibolites on a Ce vs. Nd diagram. In the gneisses the age and isotopic evidence suggest that the two terranes had distinct histories until after 2520 Ma and by 2420 Ma ($^{40}Ar/^{39}Ar$ age of muscovite in the sheared margin of the schist belt). Based on these data Hanson suggested that the schist belt probably represents the site of accretion of diverse fragments (terranes) to the margin of the craton in the latest Archean, possibly as an Archean analog to the Phanerozoic North American Cordillera.

In discussion, Newton noted that the isograds in the Dharwar Cratons cross essentially E-W, but the structures (including the proposed Kolar suture) are essentially N-S. He asked Hanson how these two facts could be reconciled. Hanson replied that the craton could have been subjected to a period of post-tectonic (static) metamorphism after ca. 2.5 Ga. Mukherjee stated that he believed that the stretching lineations in the shear zones adjacent to the Kolar Belt have steep plunges, suggesting that major movement in the shear zones was dip-slip. Mukhopadhyay, fielding the comment as the structural geologist in the JNU-Stony Brook Kolar Schist Belt group, commented that the stretching lineations in the shear zones are shallow, and that steeply plunging lineations in the shear zones are crenulations. Ramakrishnan noted that the amphibolites on the eastern and western sides of the belt are similar; he asked Hanson about the site of the actual suture. Hanson proposed that the various "packages" of rocks in the schist belt allowed for the presence of several "sutures" between unrelated rocks, such as east of the central massive amphibolites and west of the schist belt itself. Gopalan asked if there are any early structures (precollision) preserved. Hanson suggested that there may be an early foliation preserved locally in the gneisses. Anantha Iyer noted that hypersthene basalts are present in the Kolar area. Hanson was asked for a description of the stratigraphy of the supracrustal rocks in the Kolar Schist Belt. He responded by stating that because the various supracrustal units were not related to each other and were formed in diverse settings, and because the rocks in the schist belt had been isoclinally folded and refolded, a "stratigraphy" for the schist belt was meaningless. Srinivasan asked if older metapelites and carbonates could have affected the chemistry in the gneisses west of the schist belt. Hanson agreed that the chemistry of the gneisses had been influenced by interaction of magmas with older crust, but the identification of the composition and age of that older crust was currently a topic of research.

Melting and Thermal Relations in the Deep Crust
P. Morgan

This session investigated primarily petrogenetic relations associated with the deep crust, the deep ancient crust in particular. T. C. Devaraju gave an excellent geographical introduction to the session with an extensive slide review of the rocks of supracrustal origin in the amphibolite and granulite facies terrane in southern Karnataka. In addition to introducing the delegates to the metasediments in the field area of the workshop, this presentation was a timely review of the common occurrence of metasediments in amphibolite and granulite facies rocks worldwide. Models of granulite metamorphism must include a mechanism for the burial of these sediments to the depths recorded by the geobarometers in granulite metamorphism in addition to their reexposure at the surface. Unfortunately, there was not sufficient time for discussion of this paper, but the chairman reiterated the significance of the common occurrence of supracrustals in granulite facies rocks, sometimes with remarkably little deformation.

Fundamental problems with models currently used to explain the genesis and evolution of continental crust were raised by R. J. Arculus. These problems focus around the difficulty of generating the upper continental crust from a lower crustal or mantle protolith without leaving a very large, and so far undetected, volume of restite.

Discussion of this paper raised suggestions for the location of the restite of upper crustal formation, such as hot spot tracks and mafic lower crust, inferred from seismic and other geophysical evidence. These suggestions were dismissed as inadequate, or too poorly correlated with old crust, to provide a convincing genetic association. The possible role of sanukitoids in building the Canadian Shield was accepted only if they indicate a different style from that of modern processes, as sanukitoids are rare in modern environments. Discussion concluded with a general agreement that andesite, common in the Andes, is primarily a crustal melt, and that the main flux from the mantle, as seen in island arcs, is basaltic in composition. These additions do not directly contribute to continental growth.

Additional evidence to the composition of the lower crust and uppermost mantle was presented in the form of xenolith data by S. E. Haggerty. Xenoliths from the 2.7-Ga West African craton indicate that the Moho beneath this shield is a chemically and physically gradational boundary, with intercalations of garnet granulite and garnet eclogite. Inclusions in diamonds indicate a depleted upper mantle source, and xenolith barometry and thermometry data suggest a high mantle geotherm with a kink near the Moho. Metallic iron in the xenoliths indicates that the uppermost mantle has a significant magnetization, and that the depth to the Curie isotherm, which is usually considered to be at or above the Moho, may be deeper than the Moho.

Discussion of these fascinating results questioned the need for magnetization in the upper mantle with the available constraints from satellite data. Haggerty replied that the only geologically reasonable interpretation of the xenolith data requires a Curie isotherm below the Moho. It was suggested that the xenoliths may be anomalous because they do not contain CO_2 inclusions, but this question was not pursued.

Application of the principle of uniformitarianism to the Archean was discussed by K. Burke in a search for evidence of Archean-type continental margins in Archean rocks. Burke cautioned that Archean rocks represent only 2% of the current exposure of the continents, half of which is in the North American Superior Province. Care must be taken in interpreting the global tectonic significance of relatively small exposures of Archean rocks, such as South India. Andean margins were characterized by their elongate shape, magmatic associations, and isotopic signatures. Although the compositional evidence alone will always be ambiguous, it was suggested that supporting structural evidence may aid in the identification of Archean Andean margins. Andean margin remains have been recognized in the Superior Province of Canada by these criteria, and Burke suggested that the Closepet "granite" of South India may represent another example. Burke's views were not challenged.

Focusing on the Pan African age alkali granites and syenites of the South Indian Shield, M. Santosh used geochemical and REE data to deduce that these plutons were emplaced in an extensional environment with an abundant source of CO_2.

In the discussion of this paper, it was suggested that carbonatites of the same age should be considered part of the same system, as they are all related to extension associated with Pan-African collision in what is now the Indian subcontinent. In response to a caution that the data should not be extrapolated too far, and questions about age relations of some of the units, Santosh replied that the purpose of the study was only to identify dominant fluid species. The points were made that large differences in rock type with depth (level of exposure) occur in this style of magmatism, but that the important result was that the primary fluid was CO_2.

F. Barker returned the focus of the session to the comparison of Phanerozoic Andean margins and their possible Archean analogs. Presenting geochemical and isotopic data for the episodic intrusion of the elongate, continental margin Coast batholith of southeastern Alaska and British Columbia, Barker and colleagues characterized the batholith as having been formed in direct response to subduction in accreted terranes of oceanic or slope origin. Following earlier presentations on the South Indian Shield, and deviating from their abstract, Barker and colleagues concluded that there were good analogs of the Coast batholith in Archean plutonic suites.

Discussion of this paper emphasized the geochemical similarities between the Coast batholith and plutonic suites in the South Indian Shield, specifically the 2632-Ma Dod gneiss, and gneisses west of the Kolar Schist Belt. Similarities even extend to mafic enclaves in Archean gneissic terranes that are Archean analogs of pillows in the granitoid intrusives of Alaska. Tilting of the Coast batholith down to the east suggests that a depth section of several kilometers may be exposed along strike in the batholith, and it was suggested that this batholith may be one of the best in the world to study in this respect.

The session was concluded with a theoretical paper on the thermal role of fluids in granulite metamorphism, presented by P. Morgan. It was shown that for granulites to be formed in the middle crust, heat must be advected by either magma or by volatile fluids, such as water or CO_2. Models of channelized fluid flow indicate that there is little thermal difference between channelized and pervasive fluid flow, for the same total fluid flux, unless the channel spacing is of the same order or greater than the thickness of the layer through which the fluids flow. The volumes of volatile fluids required are very large and are only likely to be found associated with dehydration of a subducting slab, if volatile fluids are the sole heat source for granulite metamorphism.

Discussion of this paper emphasized that magmas are commonly associated with granulites and there is little evidence for the large volumes of volatile fluids required for the heat source. Morgan responded that magmas are theoretically the most viable heat source, and that field and laboratory studies should be oriented toward showing the spatial and temporal relationship between magmatism and granulite metamorphism. The session dispersed amidst continuing arguments about the heat source(s) for granulite metamorphism.

Fluids in High-Grade Metamorphism

R. C. Newton

The session opened with R. C. Newton's introductory talk summarizing the various models for the nature and origin of fluids in granulite facies metamorphism. Field and petrologic evidence exists for both fluid-absent and fluid-present deep crustal metamorphism. The South Indian granulite province is often cited as a fluid-rich example. The fluids must have been low in H_2O and thus high in CO_2. Deep crustal and subcrustal sources of CO_2 are as yet unproven possibilities. There is much recent discussion of the possible ways in which deep crustal melts and fluids could have interacted in granulite metamorphism. Because of the review nature of this paper, discussion was deferred by request of the speaker to an informal gathering at the morning tea hour.

J. Valley then discussed possible explanations for the characteristically low activity of H_2O associated with granulite terranes. Granulites of the Adirondacks, New York, show evidence for vapor-absent conditions, and thus appear different from those of South India, for which CO_2 streaming has been proposed. Valley discussed several features, such as the presence of high-density CO_2 fluid inclusions, that may be misleading as evidence for CO_2-saturated conditions during metamorphism.

In discussion, Chairman J. Touret commented that as time goes on, it becomes more and more clear that the origin of fluid inclusions in granulites is not simple, and interpretations *about their significance must be correspondingly more cautious. L. Ashwal then commented that much of the evidence for vapor-absent metamorphism in places like the Adirondacks depends on estimates of very low oxygen fugacity. He wondered how this conclusion is affected if the low f_{O_2} constraint is removed, possibly because oxide minerals are easily retrogressed and give false indications. Valley replied that everyone agrees that if a vapor phase were present, it would have to have been largely CO_2. There are three different CO_2 fugacity indicators that give variable and sometimes low CO_2 fugacities for the Adirondacks. This is important because low H_2O fugacity does not, in itself, necessarily imply high CO_2 fugacity. S. Wickham pointed out that some of Valley's oxygen isotope data on Adirondack anorthosites and contact marbles and xenoliths appear to show at least some exchange at their margins. He suggested that Valley could not use the compositions in the interior of xenoliths to say that metamorphism was totally vapor-absent throughout. Valley replied that the sharp isotope gradients and general lack of homogenization indicate that a vapor phase was not pervasive, even on a scale of centimeters.*

The next talk was given by Wickham, who discussed underplating, anatexis, and assimilation of metacarbonate as possible sources for large CO_2 fluxes in the deep crust. He suggested that large fluxes of CO_2-rich fluids could be generated during assimilation of refractory carbonate-rich metasediments by underplated mafic magma in the lower crust.

In the following discussion, Valley commented that carbon isotope data for high-grade marbles were not supportive of Wickham's assimilation model. The average metamorphic marble has $\delta^{13}C$ of about zero per mil. In order to get a CO_2 vapor of about -5 per mil by Rayleigh fractionation, the marble would have to be at least 90% decarbonated, which would yield only small amounts of vapor of the right composition. Wickham replied that Baertchi's 1957 compilation show many high-grade marbles with $\delta^{13}C$ as low as -10 per mil. Valley pointed out that many of Baertchi's rocks were contact marbles whose $\delta^{13}C$ could have been overpowered by exchange with magmatic carbon. R. Frost then stated his view that granulites are probably ultimately products of igneous activity, although only about 20% of a given regional granulite terrane could be caused by CO_2 exsolved from magmas. Therefore there must be other mechanisms of granulite formation. G. V. Anantha Iyer commented that the authors so far have not considered the possibility of hydrogen activity in deep crustal fluids—oxidation-reduction reactions involving hydrogen metasomatism may be at least as important in their effects as CO_2. M. Schidlowski commented that a proper mixture of graphite of organic origin and carbonate could, if mobilized together, produce a CO_2 vapor with mantle-like ^{13}C. He wondered if there were any documented cases of equilibrated graphite and carbonate. Valley replied that he and J. O'Neil have published analyses of coexisting calcite and graphite with consistent carbon isotope fractionation indicating metamorphic equilibration. L. Hollister mentioned that he has field examples of CO_2 produced by mobilization of carbonate and graphite.

T. Chacko and colleagues then presented a paper on their determinations of water activities in various granulite-facies rocks of the Kerala Khondalite Belt. Using mineral equilibria, thermodynamic data, and assumed P-T conditions of 5.5 kbar and 750°C, they calculated uniformly low a(H_2O) values of about 0.27 over a large geographic region. They suggested that these conditions were produced by the presence of abundant CO_2-rich fluids, derived either from deeper levels or from metamorphic reactions involving graphite.

In discussion, Touret asked if the apparent homogeneity in H_2O fugacity among several lithologies might merely represent similar mineralogies and mineral compositions in the various rocks. Chacko responded that this was not necessarily the case, because different independent metamorphic reactions generate H_2O vapor in different rocks. M. Raith pointed out that the textures in some of these Khondalite Belt rocks suggest gradients in H_2O activity. For instance, in Kottavattam quarry, incipient charnockites are separated from host gneisses by a several-centimeter-wide biotite-free zone. Also, local pressure and temperature gradients should be taken into consideration in these calculations. D. Waters commented that Chacko's calculations suffer from a lack of consideration of increase in temperature during the biotite breakdown reactions. The nearly constant H_2O activity result may be an artifact of having assumed a constant temperature. Chacko replied that this may not be the case, inasmuch as N. Phillips got a continual decrease of H_2O activity over an increasing temperature interval for his Broken Hills rocks. If his data are replotted assuming a constant temperature, the H_2O gradient is even stronger. Valley then voiced his approval of the kind of analysis undertaken by Chacko and colleagues. He commented that this could be a good test of whether the fluid inclusions really represent peak metamorphic fluids. If, for example, some kind of analysis of fluid inclusions gave 20% H_2O, the fluid would be a possible metamorphic fluid. If the fluid inclusions were pure CO_2, it would be an impossible metamorphic fluid.

After a tea break, E. Hansen and colleagues presented fluid inclusion and mineral chemistry data for samples from the "type" charnockite area near Pallavaram (Tamil Nadu, India). Their results indicate the presence of a dense CO_2 fluid phase, but the data cannot distinguish between influx of this fluid from elsewhere or localized migration of CO_2-rich fluids associated with dehydration melting.

In discussion, Touret commented that Hansen's photomicrographs give the impression that some of the fluid inclusion

In discussion, Touret commented that Hansen's photomicrographs give the impression that some of the fluid inclusion cavities are negative crystals, which may not necessarily indicate entrapment at peak metamorphic conditions. Touret wondered whether there were trails of inclusions with this geometry of differing density. Hansen replied that the inclusions they studied were of fairly uniform density, although the number of trails was quite small. R. Arculus pointed out that Hansen and colleagues obtained different calculated values of CO_2 activity for carbonate-scapolite-garnet veins, depending on which data set was used, Holland and Powell's or Berman's. He wondered specifically which mineral is different in the two datasets. Hansen replied that scapolite is the culprit.

D. Henry then discussed the implications of Cl-rich minerals in granulite facies rocks, citing his results from ironstones of the Beartooth Mountains, Montana. He suggested that CO_2-brine immiscibility might be applicable to granulite facies conditions, and if so, then aqueous brines might be preferentially adsorbed onto mineral surfaces relative to CO_2.

In discussion, Touret commented that a similarly remarkable variety of fluids involved in the evolution of the Beartooth granulites also appears to be the case in the granulites of southern Norway. Anantha Iyer reiterated that nobody has yet mentioned the role of H_2 in the fluids. Hydrogen is a principal gas released in the vacuum heating of amphiboles from granulites. It is the fastest-diffusing gas species, and could have important consequences in recrystallization processes.

Hollister then discussed data from several different terranes in which CO_2-rich fluid inclusions occur despite parageneses that predict the presence of H_2O-rich fluids. CO_2-rich fluid inclusions, some having densities appropriate for peak-metamorphic conditions, have been found in greenschists, amphibolites, migmatites, and hydrated granulites. Hollister suggested that there may be a common process that leads to CO_2-rich secondary inclusions in metamorphic rocks.

Touret pointed out that Hollister's paper illustrates the point that fluid inclusions form in many different ways that may be extremely difficult to unravel. Touret expressed doubt that selective trapping of CO_2 from an immiscible fluid adequately explained those cases where CO_2 and H_2O inclusions are found side-by-side. Hollister replied that late H_2O inclusions can be explained in a variety of ways, including exsolution of OH from quartz or feldspar during cooling. Wickham commented that the amount of H_2O dissolved in the quartz structure is very small. It couldn't be enough to account for the retrogressive minerals that often accompany H_2O inclusions in high-grade rocks. Valley suggested that loss of H_2O from pore fluids by rehydration reactions is a possible means of getting very CO_2-rich fluid inclusions. Newton asked if the P-T reaction biotite + quartz + graphite = orthopyroxene + liquid + CO_2-rich vapor, which Hollister showed, was a calculated equilibrium. Hollister replied that it was not; it was deduced from petrography of British Columbia granulites and the P-T location was inferred from the metamorphic conditions.

After a lunch break, Waters gave an unscheduled presentation entitled "Dehydration Melting and Formation of Granulite Facies Assemblages." He illustrated his points with examples from the granulite terrane of Namaqualand, South Africa.

In the discussion, J. Percival referred to Waters' pictures of partial melt segregation, which showed orthopyroxene crystals in the middle of melt patches. He wondered if a more normal relation for a restite phase would be dispersal throughout the wall-rock; i.e., is it possible that the orthopyroxene precipitated from the liquid phase? Waters replied that the only necessary relation between restite and melt is that they are closely associated. The orthopyroxene could have merely recrystallized by the melt flux without being largely dissolved at any time. Raith asked why there is apparently a gradient in grain size going from host-rock to charnockite lenses in the incipient charnockites. Waters reiterated that the melt fluxes recrystallization where melting occurs, which might have been always localized. Frost asked what the heat source was for Namaqualand metamorphism. Waters voiced his belief that it was magmatic overplating. The crustal thickening produced increasing pressures during the late stages of metamorphism. Wickham asked what triggered the melting locally if the melt patches are nearly isochemical with the host gneiss. Waters stated that a small amount of fluid infiltration or a small compositional anomaly started the melting, which then grows and continues to absorb water.

In the next talk, M. Santosh discussed fluid inclusion and petrologic characteristics of South India granulites and their bearing on the sources of metamorphic fluids. This paper served as a review and an introduction to the next paper by D. Jackson. Discussion was deferred until after presentation of the second paper. Jackson then presented carbon isotope data from gases extracted from fluid inclusions in South Indian granulites. The uniformly low $\delta^{13}C$ values (-10 ± 2 per mil) and the greater abundance of CO_2 in the incipient charnockites are suggestive of fluid influx from an externally buffered reservoir.

In discussion, D. Jayakumar pointed out that some of the samples analysed are from the Madras type charnockite area. He wondered if it were possible that many of the samples represent charnockites that had a different mode of origin from the more usual massif-type charnockites. Jackson agreed that he and colleagues may need a different mechanism for *the massif charnockites, perhaps one not so rich in fluids. Valley asked about the peak decrepitation temperature range of the CO_2-rich inclusions, and Jackson replied that the range was 500–700°C, determined by optical examination of the heated charnockites. Wickham commented that it seemed likely to him that a deep-seated lithospheric source of the CO_2 fluids in inclusions is necessary because of the isotopic composition and uniformity. Raith stated that there could have been other controls on the isotopic composition. For instance, precipitation of graphite from a fluid derived from oxidation of organic carbon would make the carbon isotopically heavier in the fluid. Jackson replied that this idea could be tested by estimating the amount of graphite necessary to produce CO_2 with −10 to −8 per mil $\delta^{13}C$ from a fluid derived from organic carbon. C. Schiffries commented that some of the sources of error in isotopic analyses that Jackson did not mention are mass spectrometer background and pyrolysis of graphite. Jackson assured the audience that these kinds of error were taken into account. Touret stated that there will always be problems of interpretation of the mass spectrometer analyses in this kind of fluid inclusion work until we can get analyses of individual fluid inclusions.*

G. Sisson then discussed the possible role of boron in granulite facies metamorphism. The depletion of some granulites in B could be explained by partitioning of B into a fluid or melt phase. There is also experimental data suggesting that B addition can lower the granite solidus. Sisson described her work on these effects in the Chugatch Metamorphic Complex of Alaska.

In discussion, Touret pointed out that some granulites have high B contents, such as the kornerupine occurrences. Newton commented about Sisson's "wicking" process to explain CO_2-rich fluid inclusions, in which immiscible H_2O is separated out from a two-phase inclusion by capillary action. He asked if it were possible that some of the CO_2 was slab-derived from sediments subducted under the metamorphic zone. Sisson replied that there isn't much carbonate in the low-grade trench-fill sediments exposed in the Chugatch area. K. Burke remarked that marine carbonate is usually present in subduction packages. Arculus asked if there is any evidence from B isotopes on recycling of B. Sisson replied that the expected boron fractionations have not yet been worked out.

After a break for tea, J. Morrison described her work on postmetamorphic effects in the anorthosites of the Adirondacks, New York. Calcite-chlorite-sericite assemblages occur as veins, in disseminated form and as clots, and document retrograde fluid infiltration. These features are associated with late-stage CO_2-rich fluid inclusions. Stable isotope analyses of calcites indicates that the retrograde fluids interacted with meta-igneous and supracrustal lithologies, but the precise timing of the retrogression is as yet unknown.

In discussion, Touret commented that Morrison's petrographic demonstration of retrograde textures is unambiguous. He pointed out, however, that one must be careful that apparent high densities of associated fluid inclusions are not merely due to N_2 admixture. Morrison responded that such effects would apply to any supposedly primary fluid inclusions in granulites, since the same techniques were used in her study as in most fluid inclusion studies of granulites. Santosh asked if the calcite-bearing veins cut across quartz grain boundaries, and pointed out that high-grade fluid inclusion trails never intersect grain boundaries. Morrison replied that the postmetamorphic fluid inclusion veins she studied did not cut across quartz crystal boundaries. Hollister commented that one thing that remains unexplained is the apparent increase of fluid inclusion density with metamorphic pressures, as in South India.

Raith then discussed the characterization of fluids involved in the gneiss-charnockite transformation in southern Kerala. Using a variety of techniques, including microthermometry, Raman laser probe analysis, and mass spectrometry, Raith concluded that the CO_2-rich, N_2-bearing metamorphic fluids in these rocks were internally-derived rather than having been introduced by CO_2-streaming.

Newton asked Raith if retrograde breakdown of biotite to chlorite could have given N_2 for fluid inclusions by release of ammonium component. Raith replied that the biotite in these rocks is not generally retrogressed to chlorite. Touret commented that the large range of fluid inclusion densities indicates that many of them are not unmodified primary fluids. Anantha Iyer asked about the processes that operate on organic compounds to give graphite. Raith replied that these were destructive distillation reactions similar to those that make coal.

C. Srikantappa then described the retrograde features of high-pressure charnockites in the Nilgiri Hills. These effects occur along shear planes and are also associated with pegmatite veins, and appear to be related to shear deformation associated with the Bhavani and Moyar shear belts, which surround the Nilgiri Hills.

In discussion, K. T. Vidyadharan asked if Srikantappa considered that escape of CO_2 and H_2O through shear zones is a general feature of terranes undergoing metamorphism. He replied that there is much evidence that the motion of fluids through metamorphic rocks was commonly governed by shear zones. D. Mukhopadhyay asked if there were any data that give the nature of fault movements along the Moyar-Bhavani shear zone, and if so, how much? Raith replied that the offsets in the field are strike-slip, and he had no data on the absolute amount of movement. N. Krishna Rao asked if Srikantappa thought that fluids play a generally important *role in the retrogression of granulites. Srikantappa replied that there is a great deal of evidence that this is generally true.*

The final talk of the session, by Touret, was an excellent summary on the nature and interpretation of fluid inclusions in granulite facies rocks. He showed many spectacular photomicrographs illustrating the textural varieties of fluid inclusions. He then discussed how fluid inclusion data could (and in some cases could not) be interpreted to deduce uplift paths of high-grade metamorphic terranes.

In discussion, D. C. Mishra asked Touret if magmas were indeed the most likely source of heat for granulite metamorphism, then what are the main possibilities for putting magmas into the deep crust? Touret replied that the main possibilities are as mantle-derived magmas, possibly during crustal accretion episodes, and melting of deeply buried sediments. S. Haggerty pointed out that the heat transporting ability of mantle-derived fluids is another possibility. There are metasomatized horizons in the mantle that could be sources of volatiles. There is a carbonate-metasomatic layer zone at about 60-km depths from which CO_2 could be driven by thermal action. Touret added that carbonatite magmas emplaced in the lower crust are another source of volatiles. Some of his Norway granulites contain mineral inclusions that he interprets as carbonatite melt inclusions. At this point the session was adjourned by Co-Chairman C. Leelanandam.

Metamorphic Petrology and Tectonics
J. A. Percival and K. Burke

K. Mezger outlined the rationale for constructing pressure-temperature-time (P-T-t) paths by using U-Pb dating of garnet produced in thermobarometrically sensitive reactions. In an example from the Pikwitonei granulites of the Northwestern Superior Province of the Canadian Shield, garnets were formed at 2744–2742 Ma, 2700–2689 Ma, and 2605–2590 Ma, the latter events coinciding with times recorded by U-Pb zircon systems. Garnet grew during metamorphism at 6.5 kbar, 630–750°C and later at 7.2–7.5 kbar, 800°C; the later metamorphism apparently did not exceed the U-Pb closure temperature. The resultant P-T-t path is counterclockwise, with late isobaric cooling, interpreted to result from magmatic heating at an Andean margin.

In discussion, L. Ashwal asked if garnet closure temperatures were known for Sm-Nd and Rb-Sr. The speaker replied that these rocks would be suitable for such a determination and that workers in Argentina had estimated 650°C for Rb-Sr closure. K. Burke wondered if the Pikwitonei represented greenstone belt roots exhumed during the Thompson collision and Mezger replied that the deep parts of the Cross Lake belt are represented, but that rutile dates indicated uplift before the Proterozoic tectonism at about 2400 Ma. D. Henry suggested that the U-Pb garnet ages might be a mixture acquired through growth during different reactions or even polymetamorphism. The author stated that garnets had undergone Ca-Fe-Mg diffusion during growth, but that the larger ionic radii for U-Pb prevented such effects. M. Raith, impressed by the 1-2-Ma resolution of the technique, wondered about inclusions in garnet and if old lead might have been swept out during garnet homogenization. Mezger indicated that only homogeneous garnets had been analysed. J. Valley asked if U and Pb abundances were high enough to detect on the SHRIMP (super high-resolution ion microprobe) and the speaker estimated that only 0.5 counts per minute would arise.

Raith presented data on pressure and temperature determinations from the Nilgiri Hills. About 70 samples were analysed by probe and several calibrations of garnet-pyroxene thermometry and barometry applied. Most calibrations gave considerable scatter; however, a new calibration by Bhattacharya, Raith, Lal, and others, accounting for nonideality in both garnet and orthopyroxene, gave consistent results of 754° ± 52°C and 9.2 ± 0.7 kbar. On the regional scale, a pressure increase of 6.5–7 kbar in the SW to 11 kbar in the NE was related to block tilting. A continuous pressure gradient into the Moyar shear zone suggests that the zone is not a suture juxtaposing unrelated blocks.

In discussion, G. V. Anantha Iyer asked about the effect of pelite-charnockite-metabasite compositional variation on calculated P-T. Raith replied that pelites are rare in the Nilgiris, but that present activity models are probably inadequate for large bulk compositional differences. R. Arculus wondered why T did not increase with P above 750°C and if geochemical depletion correlated with P. The speaker suggested that during cooling the thermometers reset and the barometers did not; high-P rocks are not depleted with respect to lower-P samples. J. Touret suggested that above 750°C, temperature was buffered by partial melting and the author agreed to this possibility. C. Leelanandam asked if the southern block had been subducted northward and Raith offered no speculation. D. C. Mishra wondered whether a suture could be located to the south and Raith replied that a suture is demanded by D. Buhl's Rb-Sr data, which suggest a <3.0-Ga crustal residence age for the Nilgiris, in contrast to the >3.4-Ga age of the Dharwar Craton. D. Pattison mentioned that his recent experimental recalibration of the garnet-clinopyroxene thermometer reduced temperature by about 100°C in many cases.

G. R. Ravindra Kumar then discussed the origin of the Kerala khondalite belt, consisting of interlayered garnet-sillimanite-graphite-cordierite schists, migmatitic gneisses, and leptynites, bounded by massif charnockite on the northeast. Charnockite patches occur in low-P structural settings as well as adjacent to granite dikes. Metamorphic pressure was generally 5–6 kbar, with slightly higher values toward the massif terrane. Based on major elements and oxygen isotopes, the khondalites were interpreted as a heterogeneous sedimentary succession and the charnockites as meta-igneous rocks. An evolutionary sequence was proposed, involving derivation of sedimentary material from a continental source and subsequent closure of the basin, followed by metamorphism, migmatization, and rapid uplift.

In discussion, M. Ramakrishnan questioned the extent of the Kerala belt portrayed, suggesting that rocks north of the Achankovil shear zone should be included. The authors responded that there are distinct lithological differences between the two regions and was supported by C. Srikantappa. C. Schiffries inquired about the validity of using barometry based on fluid inclusions, without knowing that entrapment was peak metamorphic. M. Santosh replied that temperatures were extrapolated from the fluid inclusions along reasonable isochores. Burke mentioned the 560-Ma monazite age on charnockite determined by Buhl and wondered about the possibility of Pan-African metamorphism and subsequent juxtaposition along Cordilleran-scale strike-slip faults.

After a tea break, T. M. Kusky presented the first of four talks on tectonics. He reported on detailed field studies of selected areas in the greenstone belts of the Slave Province of Canada. This area has long been cited as a type area by supporters of the (now generally abandoned) rift model of greenstone belts (see abstract by K. Burke and C. Sengor in *Workshop on the Tectonic Evolution of Greenstone Belts*, edited by M. J. deWit and L. D. Ashwal, LPI Tech. Rpt. 86-10). Kusky showed that a plate tectonic interpretation accounted more successfully for the regional geology and identified four "terranes" that had experienced complex divergent and convergent histories between 2.7 and 3.4 Ga. A dismembered ophiolite has been identified and a late episode of widespread granitic intrusion has been recognized.

In discussion, Arculus asked about the depths exposed in this terrane. Kusky replied that about 15 km were visible. J. Percival asked how this interpretation of Slave Province tectonics related to P. Hoffmann's migrating arc model. Kusky replied that his interpretation had some features in common with Hoffmann's model. Arculus asked about the tectonic environment represented by the late granites. Kusky replied that perhaps these might represent a genuinely distinctive Archean phenomenon related to greater heat generation. At late stages of orogenic activity mountain belts might have suffered sufficient internal heating to partially melt. Burke expressed doubt as to whether the amount of "block and fragment" ("terrain" terminology of others) assembly described could be achieved without leaving some evidence of strike-slip motion. Kusky said they saw none.

W. S. F. Kidd then presented his paper, which illustrated how late Archean tectonics could be seen to have operated in the Slave Province. Lithospheric thinning and stretching, with the formation of rifted margins (to continental or island arc fragments), and lithospheric flexural loading of the kind familiar in arcs and mountain belts could be discerned.

In discussion, Mezger commented that now that evidence of plate tectonic activity is being so widely described from the Archean, it is surprising that blueschists remain undescribed. Perhaps the Slave Province would be a good place to look, at least for blueschist mineral pseudomorphs. R. Srinivasan asked Kidd what kind of model he could envisage that accounts for the dying-out of volcanic activity as seen in the Dharwars. It is hard to understand the absence of volcanic rocks from the Middle Dharwars.

V. R. McGregor then discussed granulite metamorphism in the neighborhood of Godthaab, West Greenland. After expressing his appreciation of the opportunity of seeing the classical exposures of South India, he described three distinct episodes and occurrences of granulite metamorphism in West Greenland: (1) The oldest fragmentary granulites occur within the 3.6-Ga Amitsoq gneisses and appear to have formed 200 Ma after the continental crust in which they lie. Spatially associated rapakivi granites have zircon cores as old as 3.8 Ga, but Rb-Sr, whole-rock Pb-Pb, and all other systems give 3.6 Ga, so these granulites apparently represent a later metamorphic event. (2) 3.0-Ga granulites of the Nordlandet Peninsula NW of Godthaab, developed immediately after crustal formation in hot, dry conditions, are carbonate-free, associated with voluminous tonalite, and formed at peak metamorphic conditions of 800°C and 7–8 kbar. Synmetamorphic trondhjemite abounds and the activity of H_2O has been indicated by J. Pilar (of Tarney's group) to have varied greatly. A possible mechanism of origin resembles that suggested by P. R. Wells, and involves accretion of tonalites, which heated the material beneath, causing partial melting and extraction of water. This heat source could possibly have been subduction-related emplacement of calc-alkaline magma into the middle crust. (3) 2.8-Ga granulites south of Godthaab, originally described by Wells, lie to the south of retrogressed amphibolite terranes. Prograde amphibolite-granulite transitions are clearly preserved only locally at the southern end of this block, near Bjornesund, south of Fiskenaesset. Progressively deeper parts of the crust are exposed from south to north as a major thrust fault is approached. Characteristic "big hornblende pegmatites," which outcrop close to the thrust in the east, have been formed by replacement of orthopyroxene. McGregor noted that comparable features were not seen in South Indian granulites during the Field Workshop. Features of the 2.8-Ga granulites are: (a) they formed from cool, dry protoliths

150–200 Ma after the crust that contains them; (b) they contain no carbonate; (c) they are associated with syngranitic "rapakivi" (*sensu-lato*) ferrodiorite sheets intruded at P-T conditions well below the amphibolite-granulite transitions; (d) patchy outcrops (like those at Kabbaldurga) occur; and (e) little evidence of partial melting is seen in the area. Mechanisms of origin for the 2.8-Ga granulites must accommodate the existence of both a dry protolith and the rapakivi ferrodiorites. Possibilities include dry melting of deep crust contaminated by basic magmas, underplating by basic magmas, CO_2 infiltration or the proximity of a heat source during the CO_2 flux, and underplating. McGregor concluded that no one mechanism accounts for the origin of all granulites in West Greenland. Various processes have interacted in different ways, and what happened in individual areas must be worked out by considering all possible processes.

In discussion, Ashwal asked if his 2860 Ma Sm-Nd age for the Fiskenaesset anorthosite indicated an association with the granulite-forming event. McGregor replied that this was doubtful. Touret asked whether the "Kabbaldurga-like" outcrops showed depletion comparable to that at the type locality. McGregor replied that they were not yet studied. Anantha Iyer drew attention to big hypersthene-bearing rocks near Sittampundi. R. C. Newton suggested that massive isotope resetting might also be invoked for the Nilgiri terrane of South India, but P. Taylor emphasized that total eradication of the isotopic record was not possible. S. Wickham suggested that carbonate rocks might lie below the granulites. McGregor pointed out that exposure was very good, and no carbonates were seen, but that more geochemical work could help reveal more about the origin of the extensive granulites in West Greenland.

Percival then presented the last paper in the session. The Ashuanipi granulite terrane of the Canadian Superior Province has now been studied in detail, and an origin through self-melting of a 55-km-thick accretionary wedge seems possible.

In discussion, Touret suggested that fluid inclusions in phases such as apatite might help to reveal the history of the rocks. Wickham asked why there was simultaneity of granulite formation, subduction being a continuous process. Burke wondered if the end of the subduction process might be recorded, and L. Hollister pointed out that he had made a relevant calculation about the thermal effects of subducting buoyant material for Cenozoic times. Chairman M. Raith adjourned the session at this time.

Granulite Terranes: Characteristics and Transitions

J. Morrison

M. Raith opened the afternoon session by addressing the nature of the chemical changes that occur across the amphibolite to granulite transition in a single sample from the Kabbal quarry. The transition from hornblende-biotite-bearing granodiorite gneiss to charnockite is apparently accompanied by an increase in K, Rb, Ba, and Si, and a decrease in Fe, Mg, Ca, and Ti. Mineralogic changes across the transition include a 12% increase in K-feldspar, 6% increase in quartz, and 1% increase in orthopyroxene. Decreases of 10% in plagioclase, 6% in hornblende, 2% in biotite, and 1% in Fe-Ti oxides also accompany the transition. Citing the presence of CO_2-rich fluid inclusions in the charnockite, as well as the chemical and mineralogic changes across the transition, Raith interprets the transition to reflect K-metasomatism in response to infiltration of externally-derived carbonic fluids. He concludes that the fluids were probably deep-seated in origin and were "tapped" from depth by shearing, and hence the occurrence of charnockites is structurally controlled by shear zones.

In the discussion that followed, F. Barker pointed out that the composition of the charnockite is intermediate between hbld-biot granodiorite and the aplite. Hence rather than invoking metasomatism, the apparent major and minor element changes could easily be accounted for by incorporating the aplite into the "pre-charnockite" amphibolite facies gneiss. In this case the only difference between the amphibolite and charnockite is the H_2O/CO_2. B. R. Frost pointed out that Raith's interpretation is dependent on the assumption that a CO_2 phase was present. Frost argued that the data are perfectly consistent with the extraction of a melt phase and in the absence of strong evidence for the presence of a CO_2-rich fluid, melt extraction must be considered as a likely explanation. Finally, R. C. Newton emphasized the variable scales upon which the "charnockitization process" operate. Raith described CO_2-flooding on the hand sample scale, and Newton argued that the same fluid-dominated process occurs on huge scales as well.

The second talk was a delightfully entertaining discourse by G. V. Anantha Iyer. He explained that "my specialization is generalization" and emphasized the importance of the "big picture" in geology. The "big picture" of the Indian crust contains essentially three components: (1) the upper crust, which is composed of platformal sedimentary sequences (including banded iron formations), (2) the middle crust, which is represented by the Peninsular gneiss, and (3) the deep crust, which is composed predominantly of charnockites. Anantha Iyer addressed the charnockitization controversy by stating that "CO_2 is absolutely *not* essential for charnockite formation," and suggested rather that molecular hydrogen movements play an important role.

The third talk by R. Sharma included a description of the granulites from the NW Indian Shield. The granulites are found with the 3.5-Ga amphibolite facies banded

Gneissic Complex. Detailed barometry and thermometry suggest a counter-clockwise pressure-temperature-time path for formation of the Sand Mata granulites, which is similar to that of the South India granulites.

In the discussion, Newton inquired about the age of the granulites. Sharma responded that the best age estimate is ~3.5 Ga. K. Mezger pointed out that in calculating the P-T-t relations from rim compositions, if the calculations are done at lower temperatures, then the resultant P-T-t path would most likely be isobaric.

The final talk of the afternoon was given by J. Myers, and included an updated summary of geological and geochronological studies in the Western Australian Shield. This terrane bears many similarities to the Indian Shield since they were neighboring parts of Gondwanaland. Western Australia consists of two cratons (Pilbara and Yilgarn) and four orogenic belts (Capricorn, Pingarra, Albany-Fraser, and Patterson), as well as some relatively young (1.6 to 0.75 Ga) sedimentary rocks. The two cratonic blocks are both older than about 2.5 Ga, and the orogenic belts range in age from 2.0 to 0.65 Ga.

Anorthosites and Related Rocks

D. J. Henry

The session opened with an overview of anorthosites by L. D. Ashwal. He classified anorthosites into six types: (1) Archean megacrystic, (2) Proterozoic massif-type, (3) stratiform, (4) oceanic, (5) inclusions, and (6) extraterrestrial. He then discussed and attempted to dispel some of the anorthosite "mythology," such as the existence of a distinct, catastrophic anorthosite "event" in the late Proterozoic, the misconception that anorthosite is a major constituent of the lower continental crust, and the misconception that Archean anorthosites represent metamorphosed equivalents of mafic layered intrusions such as Bushveld or Stillwater. He offered a general statement about the origin of *all* anorthosites: They are cumulates of plagioclase from mantle-derived basaltic magmas.

In discussion, F. Barker pointed out that an additional category of anorthosites might be those found in back-arc settings. Ashwal agreed, but pointed out that this type commonly occurs as inclusions in calc-alkaline plutonic rocks. G. V. Anantha Iyer asked about the origin of so-called "monzo-anorthosites." Ashwal replied that these represent anorthositic rocks that have been extensively contaminated by infiltration of later granitoid materials.

C. Leelanandam then reviewed the anorthosite and alkaline rock localities in the Precambrian Shield of Peninsular India. There are approximately 50 localities of such rocks, generally restricted to the Eastern Ghats mobile belt. The alkaline plutons are typically confined to the margin of the Eastern Ghats. The anorthosites are all <500 km^2, but many exhibit similarities to one another. Leelanandam suggested that the anorthosites are associated with cryptic sutures, and are thought to have originated as a result of ponding of basaltic magmas. He drew an analogy between the Eastern Ghats belt and the Grenville Province of the Canadian Shield.

In discussion, M. Santosh asked if there is an association between the syenites and gabbros. Leelanandam replied that the association is spatial, but not necessarily genetic.

R. A. Wiebe then reported on the metamorphism of the Oddanchatram anorthosite, Madurai district, Tamil Nadu, India. This body was intrusive into a 2.6-Ga granulite terrane and contains many inclusions of the country rock near the margins. It has textural and compositional features typical of Proterozoic anorthosites, but is deformed and metamorphosed after emplacement. Geothermobarometry suggests maximum metamorphic conditions of 900°C and 10–11 kbar, but there is some evidence from grain edges for later conditions of 600–800°C and 6–7 kbar. Wiebe suggested that the mid-Proterozoic crust in this region was roughly 75 km thick as a consequence of continental collision and underthrusting of the eastern margin of the South India Shield below a converging continent.

In discussion, J. Valley asked Wiebe if he thought the presence of anorthosite dikes was compatible with the general model that anorthosite is emplaced within the crust as a crystal mush. Wiebe replied that leuconoritic dikes probably represent liquids that have become abnormally feldspathic by resorption of suspended plagioclase in periodically replenished magma chambers. They are derivative liquids, not parental ones, and seem to be restricted to younger plutons in a complex. Plagioclase accumulation (from a basaltic parent?) is probably the dominant process to produce pure anorthosites.

The next talk was given by J. M. McLelland, who presented an update of the recent U-Pb isotope geochronology and models for evolution of some of the meta-igneous rocks of the Adirondacks, New York. Uranium-lead zircon data from charnockites and mangerites and on baddeleyite from anorthosite suggest that the emplacement of these rocks into a stable crust took place in the range 1160–1130 Ma. Granulite facies metamorphism was approximately 1050 Ma as indicated by metamorphic zircon and sphene ages of the anorthosite and by development of migmatitic alaskitic gneiss. The concentric isotherms that are observed in this area are due to later doming. However, an older contact metamorphic aureole associated with anorthosite intrusion is observed where wollastonite develops in metacarbonates. Xenoliths found in the anorthosite indicate a metamorphic event prior to anorthosite emplacement. The most probable mechanism for anorthosite genesis is thought to be ponding of gabbroic magmas at the Moho. The emplacement of the anorogenic anorthosite-mangerite-charnockite suite was apparently bracketed by compressional orogenies.

In discussion, K. Burke inquired about the age of the older metamorphism. McLelland replied that this took place some time before 1320–1420 Ma, based on dates of foliated inclusions in meta-igneous granitoids. S. Haggerty asked about the geochemical characteristics of the mantle lithosphere during anorthosite genesis, particularly in relation to density and depletion. Ashwal responded to this question by stating that isotopic data from Grenville Province anorthosites indicate derivation from depleted mantle. The apparently enriched signatures of anorthosites northwest of the Grenville Front in Labrador were produced by assimilation of early Archean basement gneisses. R. Arculus commented that in many anorthosite bodies, orthopyroxene is the main mafic phase. This is not a normal sequence of crystallization. He wondered if this was due to unusual source characteristics or possible contamination. McLelland responded that normal picritic basalts will differentiate olivine and clinopyroxene and push the residue to the appropriate composition. Ashwal added that orthopyroxene-bearing anorthosites have higher initial Sr ratios and lower initial Nd ratios compared to olivine-bearing ones, suggesting that crustal contamination may be an important factor.

B. R. Frost then addressed what he termed "the granulite uncertainty principle," which states that it is difficult or impossible to determine with certainty the maximum P and T that a granulite has experienced. Also, geochemical fingerprinting cannot always be used reliably in the nebulous region that is transitional between metamorphic and igneous environments. Ion exchange thermometers are typically useful to approximately 800°C in slowly cooled plutonic rocks unless one uses a reintegration technique on unmixed minerals, or unless a metastable mineral assemblage can be observed. Frost argued that in most granulites, fossil temperatures are typically obliterated by reequilibration and/or deformation during slow cooling. Granulite metamorphism may be further complicated by the common association with igneous activity. The previously-used geochemical indicators such as high K/Rb ratios and LIL depletion may not be strictly the result of granulite facies metamorphic depletion, but also may result from igneous processes, which depend on bulk and mineral compositions and on the mineralogy of the protolith. Detailed geologic mapping will be the ultimate arbitrator of whether a given geochemical signature is the result of igneous or metamorphic processes.

J. Percival commented that noncontacting mafic minerals may provide a fossil thermometer giving 200–300°C higher temperatures than phases not in contact. He wondered if there was a rationale for this procedure. Frost replied that the resetting of ion-exchange thermometers will be controlled by (1) diffusion of ions to grain margins and (2) transport of ions in the fluid phase from one grain to another. The second process will be strongly affected by the transport distance and the presence or absence of a fluid phase. Clearly, transport of ions (i.e., retrogression) will be favored in systems where pyroxenes are touching or where ample fluid is present. Thus, he suggested, Percival's observations were reasonable. E. Hansen commented that he and colleagues have preliminary data that indicate that high K/Rb ratios in biotites correlate with high K/Rb ratios in the whole rock. He wondered how Frost would explain this in a magmatic model. Frost responded that it is difficult to answer this question without knowing the bulk-rock and feldspar K/Rb ratios and the origin of the biotite. Magmatic biotites may have "normal" K/Rb, whereas metamorphic biotite formed from orthopyroxene + K-feldspar have higher K/Rb. Arculus asked if there are any other possible geochemical signatures. Frost replied that the data were permissive.

W. C. Phinney then reviewed the occurrences of megacrystic anorthosite and basalt in a variety of geologic settings and found that these rock types occur in a variety of tectonic settings. Anorthosites and megacrystic basalts are petrogenetically related and are found in oceanic volcanic crust, cratons, and shelf environments. Although megacrystic basalts are most common in Archean terranes, similar occurrences are observed in rocks of early Proterozoic age, and even in young terranes such as the Galapagos hotspot. Based on inferences from experimental petrology, all of the occurrences are apparently associated with similar parental melts that are relatively Fe-rich tholeiites. The megacrystic rocks exhibit a two-(or-more)-stage development of plagioclase, with the megacrysts having relatively uniform composition produced under nearly isothermal and isochemical conditions over substanstial periods of time. The anorthosites appear to have intruded various crustal levels from very deep to very shallow. The petrogenetic indicators, however, suggest that conditions of formation of the Precambrian examples were different from Phanerozoic occurrences.

In discussion, Leelanandam wondered how Phinney accounted for the absence of megacrysts in the Archean Sittampundi anorthosite complex. Phinney replied that these were likely obliterated by intense deformation and recrystallization.

In the next talk, D. A. Morrison considered the petrogenetic significance of plagioclase megacryst-bearing Archean rocks. He suggested that these developed in mid- to upper-crustal magma chambers that have been repeatedly replenished. Crystallization of megacrysts from a primitive liquid that evolves to an Fe-rich tholeiite (with LREE enrichment) is nearly isothermal and is an equilibrium process. Cumulates probably form near the margins of the chambers and liquids with megacrysts are periodically extracted and can appear as volcanics. Some flows and intrusives are found in arc-like settings in greenstone belts. Megacrystic dikes represent large volumes of melt and dike swarms such as the Metachawan swarm of Ontario suggest multiple sources of similar compositions. A complex series of melt ponding and migration are probable and involve large amounts of liquid.

In discussion, Anantha Iyer asked if electron spin resonance work has been done on the plagioclase to check for the presence of Fe^{3+}. *Morrison replied that a group from Japan is currently investigating this. Hansen wondered why these rock types are restricted to the Archean. Morrison responded that some have been found in Proterozoic terranes, and that there may be an exposure problem. Barker commented that there is a possible Triassic equivalent in the Wrangellia terrane of Alaska. This terrane contains back-arc Fe tholeiite with a 30* km^2 *anorthosite. Arculus wondered why the megacrysts were equant in shape. Morrison replied that this is probably a function of growth rate and composition. Haggerty added that rounded textures in kimberlites are due to abrasion.*

The final talk of the session was given by E. B. Sugavanam, who reviewed the structural patterns that are present in the high-grade terrane of portions of Tamil Nadu and Karnataka. The deformed charnockites and high-grade gneisses appear to be tectonically reworked and multiply metamorphosed, with layered ultramafics, shelf-type sediments, and igneous intrusives. In parts of the area there are five phases of deformation, five generations of basic dikes, and four generations of migmatization between 2900 and 750 Ma. Regional folds are isoclinal and asymmetric with NNE-SSW axial traces during the 2600-Ma charnockite-forming event. This is overprinted by an amphibolite facies metamorphism and intruded by felsic gneisses. These were later affected by a series of dike emplacements and deformation. The final significant event (at 750 Ma) was the development of deep crustal fractures and the emplacement of alkali syenite and carbonatite complexes.

In discussion, Burke asked about the similarities and differences between this terrane and western Australia. Sugavanam replied that the two are quite similar although there are fewer mafic dikes in western Australia.

Tectonics and Ages of Deep Crust

L. D. Ashwal

The first talk in this session was given by M. Ramakrishnan, who described and discussed the major tectonic divisions of the South India high-grade terrane. The Dharwar (Karnataka) Craton can be divided into two blocks separated by the linear, N-S-trending Closepet Granite, and which differ in the nature of supracrustal rocks and the amount of subsequent basement reactivation. These terranes have been interpreted to represent failed rifting with subsequent compression. To the south, an E-W-trending charnockite belt is interpreted as a deep crustal equivalent of the Dharwar terrane. To the south of the Cauvery shear zone is a distinctly different terrane consisting of a quartzite-carbonate pelite suite within migmatitic charnockite gneisses, and further south still is the Kerala khondalite-leptynite-charnockite terrane. The long mobile belt of the Eastern Ghats differs from the Keralâ terrane in that it contains, in addition, Mn-rich marbles and quartzites. Ramakrishnan argued that the distinctive shear zones in the Precambrian of South India do not represent sutures, but instead formed by intracontinental reactivation of preexisting faults.

In discussion, R. C. Newton asked about the sense of shear in the N-S-trending shear belts of the Dharwar Craton. Ramakrishnan replied that this was difficult to determine, since these shear belts show mostly vertical rather than lateral displacements. K. Gopalan asked if the geology of South India could be traced across into other continents. Ramakrishnan stated that some of the younger ages could be correlated with Pan-African events, but certainly more isotopic work is needed to make further correlations. Newton asked if the high-grade terranes were separated everywhere from the cratonic areas by the Closepet Granite, and Ramakrishnan stated that we cannot be sure if all pink granites can be correlated with the Closepet until isotopic work is carried out. C. Leelanandam asked if there was a cryptic suture separating the Dharwar Craton from the Eastern Ghats, and wondered if an analogy could be drawn between this boundary and the Grenville Front of the Eastern Canadian Shield. Ramakrishnan replied that cryptic sutures could not, by definition, be identified precisely, and further pointed out that many do not consider the Grenville Front to represent a suture. K. Burke made a general appeal to the audience for additional isotopic work on South Indian rocks, stating that this might serve to answer some of the questions raised here. He then asked Ramakrishnan if he considered the Kolar Schist Belt to represent a suture. The speaker replied that in this case, a suture had been proposed on geochemical grounds, but that it was not possible to identify a specific suture line. M. Raith suggested that a suture might exist between the ~3.4-Ga Dharwar Craton and the <3.0-Ga Nilgiri Hills. Ramakrishnan stated that the 3.4-Ga rocks occur in isolated areas, and may just represent continental nucleii. Raith agreed that well-established occurrences of 3.4-Ga rocks were scarce, but feels that enough data exists to infer the existence of a widespread crustal block of this age.

K. Naha then discussed the structural features of the Peninsular gneisses and compared them with those in the charnockitic rocks. On this basis, three types of charnockite occurrences can be recognized: (1) those involved in isoclinal folds that have been later boudinaged and refolded, (2) those affected by migmatization synkinematic with early isoclinal folding, and (3) incipient charnockites formed in low-pressure zones of fold-hinges and boudin-necks (e.g., Kabbaldurga). Naha concluded that at least two, if not three, stages of charnockite formation are required by these structural data.

In discussion, Newton asked if the two stages of charnockite formation could have been very close in time, perhaps as part of a single deformational episode. Naha replied that this was not possible because fold axes of the different charnockite-forming events are at right angles. Burke commented that he was unsure about the extent to which there was evidence for two stages of folding and charnockite formation in the same areas. He wondered if separate phases of the same event could have been expressed differently in different areas. Naha responded that the features he described were ubiquitously distributed throughout the Karnataka Craton.

D. C. Mishra then discussed the regional gravity and magnetic features of the South Indian Shield. The prominent regional gravity low of 20–30 mgls over the charnockite terrane of South India, coupled with the correlation of a steep gravity gradient with a prominent shear zone to the north, can be interpreted in terms of increased crustal thickness in the South Indian high-grade terrane. There is some support for this from deep seismic sounding. The magnetic signature of the high-grade terrane is also distinctive, and Mishra argued that the Palghat-Tiruchi line might represent a Precambrian boundary such as a suture between two distinct crustal blocks.

In discussion, P. Morgan asked if any data on free-air gravity anomalies were available. Mishra replied that he had calculated isostatic anomalies, which show that the region is isostatically compensated by crustal thickening. Burke commented that he was pleased to see that regional gravity modeling was being carried out in India and that a regional magnetic map similar to that of the Canadian Shield would soon be available. He also mentioned the interest of Indian and U.S. workers in the possibility of COCORP-type deep seismic sounding. Burke then suggested that topographic anomalies such as the Nilgiri Hills are related to collisional tectonics in the Himalayas, drawing an analogy between these and the Kapuskasing feature of the Superior Province of the Canadian Shield, which may be related to a collisional event at the Nelson Front of Manitoba (see abstract by K. Burke in Workshop on a Cross Section of Archean Crust, *edited by L. D. Ashwal and K. D. Card, LPI Tech. Rpt. 83-03).*

P. Taylor then gave the first of two talks on geochronology of samples from the Indian Shield. He presented new Sm-Nd data for the Singhbhum granite, which give model ages (T_{DM}) of 3.36–3.40 Ga, essentially equivalent to ages of included gneissic remnants of the older metamorphic group (OMG) (T_{DM} = 3.35–3.41 Ga). Lead-lead and Rb-Sr ages of the granite and OMG range between 3.28–3.38 Ga. These results are considerably younger than the 3775 ± 89 Ma Sm-Nd isochron of Basu et al., which Taylor and colleagues interpret as an artifact caused by regressing two suites of unrelated rock samples.

In discussion, G. V. Anantha Iyer asked Taylor to comment on J. Longhi's warning about the need for a renewed sense of caution in interpreting Sm-Nd ages. Taylor endorsed this, and reiterated that care must be taken to ensure that samples considered for isochron construction be truly cogenetic. Gopalan asked if Taylor had attempted to obtain any mineral isochrons for these samples. Taylor replied that this was a good idea in principle, but that he and colleagues were provided only with powdered samples.

In his second talk, Taylor presented additional new isotopic data for samples from the Karnataka Craton. Samarium-neodymium data for some Peninsular Gneisses and Granites give T_{DM} ages of 3.15–3.25 Ga, some 100–150 Ma older than their Pb-Pb whole-rock ages, reflecting time differences between crystallization age and "mantle separation" age. For the Chitradurga Granite and Dharwar acid volcanics, however, T_{DM} = 2.99–3.06 Ga, whereas the Pb-Pb system gives ~2.6 Ga, suggesting a significant contribution from reworked older continental crust. Kyanite schists attributed to the Sargur supracrustal suite have T_{DM} = 3.09–3.18 Ga, indicating that deposition of at least some of the Sargur supracrustal rocks postdated the earliest phases of the Peninsular Gneisses. Lead-lead ages for the Closepet Granite (2529–2578 Ma) indicate a major tectonothermal event at about 2.5 Ga.

In discussion, K. V. Krishnamurthy asked about the apparent discrepancy between T_{DM} ages of 2.98–2.80 for Peninsular Gneisses and values of about 3.0 Ga for Chitradurga acid volcanics, which are stratigraphically younger. Taylor pointed out that Sm-Nd model ages represent the ages of the crustal sources of these volcanics, rather than the ages of eruption. Anantha Iyer asked if the ages of Peninsular Gneisses could possibly represent the time of depletion in U, Rb, and Pb during deep crustal metamorphism. Taylor replied that they could not, pointing to Raith's data for a high-grade metamorphic event at 2.53 Ga. Gopalan asked why Taylor preferred the Pb-Pb isotopic system over Rb-Sr to compare with Sm-Nd model ages. Taylor replied that Rb-Sr analyses are still being carried out, and pointed out that under ideal circumstances, data for all three isotopic systems should be obtained. Leelanandam inquired if isochron *ages could not be considered "birth certificates" of rocks. Taylor responded metaphorically that the T_{DM} model age represents the "birth certificate" of a rock's source or protolith, whereas its isochron age can be considered the time of its confirmation into adulthood!*

The final talk of the session was given by **R. Srinivasan**, who summarized the present status of Precambrian geochronology of South India. He offered support for Raith's conclusion of an extensive 3.3–3.4-Ga tonalite-forming event. Evidence that the Sargur supracrustal sequence predates this event, however, remains equivocal. The only reliably dated supracrustal rocks are the ~3.0-Ga Chitradurga acid volcanics (data of Taylor and colleagues), and these are separated from the older Bababudan supracrustals by a major gneiss-forming event. A major unsolved problem relates to the timing of the Sargur supracrustals in relation to the basal units of the Dharwar succession. Srinivasan made an appeal for more geochronological work on South Indian samples.

In discussion, Ramakrishnan questioned whether geochronology could hope to resolve the issue of the relative ages of Sargur and Dharwar supracrustals, and wondered further how a single folding episode could account for the different orientations of folds in the two units. Srinivasan referred to the work of Naha, in which these structural complexities were explained. C. Schiffries called attention to the reported Sr isotopic initial ratios of ~0.704 in ~2.8-Ga rocks, and wondered if these were interpreted in terms of enriched mantle or crustal contamination. Gopalan stated that these were old data with large uncertainties, and that further analyses would be needed to distinguish these possibilities. Raith commented that there was no evidence from Buhl's isotopic work for two separate metamorphic events. Srinivasan referred to Naha's structural evidence for multiple charnockite-forming events, and pointed out that these should be able to be resolved isotopically. At this point, Chairman K. Gopalan adjourned the session.

ABSTRACTS

GNEISS-CHARNOCKITE-GRANITE CONNECTION IN THE ARCHAEAN CRUST OF KARNATAKA CRATON, INDIA. Anantha Iyer G.V. Geochemistry Laboratory, Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore 560012

The Peninsular gneissic complex of tonalite-trondhjemite-granite composition unconformably underly the Proterozoic platformal and geosynclinal Dharwar Supracrustal succession in Karnataka Craton of Southern Indian shield. Isotopic work and geochemical considerations indicate that the Peninsual gneiss components of central and southern Karnataka Craton were generated by mantle-derived magmas between 3200-3000 Ma |1|. The Pb-isotopic and U-Th element compositions reveal that conditions of extreme granulite grade metamorphism were not attained at the time of Archaean crust emplacement in the craton. However, the uplifted deep-level high pressure "massif" charnockites of B.R. Hills severely depleted of U, Th, Pb and Rb |2| indicate conditions of extreme granulite grade metamorphism attained. Halagur charnockites recording high-pressure conditions of granulate grade metamorphism |3| presumably an extension of B.R. Hills charnockites yield Rb/Sr whole-rock isochron age of 2845 Ma with an initial ratio of 0.7040. This early metamorphic event does not coincide with Archaen crust forming event in the craton but coincides with U-Pb date of 2844 Ma recorded by the zircons separated from Kabbaldurga charnockite from the transition zone at the southern end of the Closepet granite |4|.

The Closepet granite, the largest linear batholith in the craton geochemically similar to Kabbaldurga granitic charnockite is reported to be formed by 20 percent batch melting of tonalite charnockite source that contained hornblende and garnet |5|.

A close examination of Peninsular gneiss quarries of Bangalore in eastern Karnataka show evidence for the inclusions of unmodified "exploded" older migmatite gneiss enclaves within the homogeneous weakly foliated penetrative younger granites. The gneissic enclaves yield Rb/Sr whole-rock isochronage of 2950 Ma with initial ratio of 0.7057. The younger intrusive granites which host these older gneiss enclaves record Rb/Sr whole-rock isochron age around 2600 Ma with initial ratios 0.7010 to 0.7032 indicating an anomalous mantle or depleted crustal source for the granites |6|. It is interesting to note that biotites separated from the gneiss enclaves yield Rb/Sr mineral date close to 2600 Ma while those from the younger granites record close to 2300 Ma the late thermal events recorded in the gneissic terrain of Bangalore.

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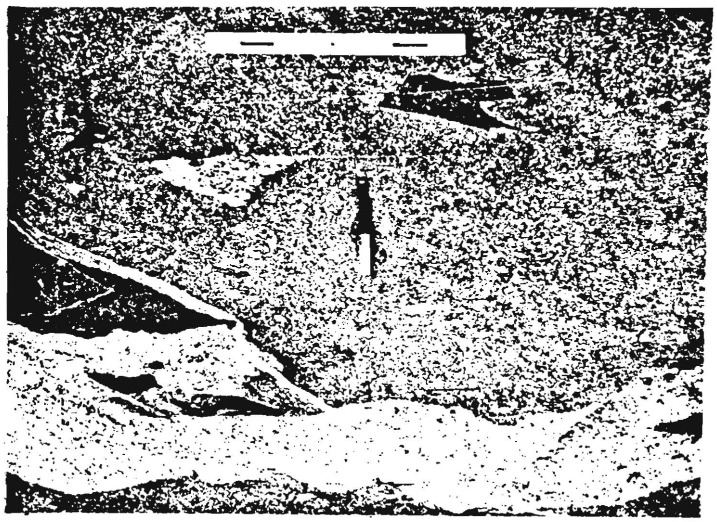

Fig. 2950 Ma old migmatite enclaves in 2600 Ma intrusive granites, Bangalore gneiss quarries.

CRUSTAL GROWTH-SOME MAJOR PROBLEMS

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The genesis and evolution of the continental crust are first-order geologic problems which remain unresolved. We still face several difficulties with respect to obtaining fundamental data necessary for solving the problems in the form of the composition and structure of the deep crust, and the nature of the crust-upper mantle boundary. While it is clear from a number of different approaches that the upper continental crust is generally of granitoid composition, the processes of upper crust production from middle and lower crust are unfortunately still obscure given the difficulty of inverting the geochemical data obtained on minimum and near-minimum melt magmas to the bulk composition of the sources. Thus it seems that the hope of using the granite cycle as a geochemical probe of the middle and lower crustal source regions is not going to be fulfilled, and other methods need to be employed. This is not to deny the use of granite geochemistry as a constraint on the isotopic spectrum of the source components and time-integrated parent/daughter isotopic ratios of these components.

The other major lines of evidence both direct and indirect that we have for the nature of the lower continental crust are: 1) exposed "deep crustal" segments; 2)xenoliths brought up in explosive, fast-moving alkalic igneous rocks; and 3) geophysical evidence (seismic wave travel times, electrical conductivity, gravity and the density-composition relations inferred from these data)

There has been considerable debate in the literature concerning the true nature and relevance to normal lower crust of uplifted slices of the continental crust that have been metamorphosed at high grades. For example, recent estimates of the P-T maxima reached by para- and orthogneisses of the Ontario (Canada) Grenville province are 10 - 12 kbar and approximately 800^{o}C, which would allow these materials to have been subjected to the conditions prevailing at the base of the normal thickness of continental crust. Nevertheless, there is still a thickness of some 30 - 40 km of crust beneath the present-day exposed Grenville and the exposed gneisses would appear to have been "middle" crust in some overthickened sequence about 1.2 Ga ago. A plausible mechanism for a) subjecting supracrustals to lower crustal conditions; b) allowing these to be exhumed to the surface is a Himalayan-style continent-continent collision, erosion and rebound. The conclusion therefore is that the Grenville terrain itself is not a direct sample of normal lower continental crust.

Studies of lower crustal xenolithic material have been increasing in number in recent years because of the difficulties encountered in other, large scale approaches. Although these studies are plagued by the minute size of sample, possible misrepresentative sampling of the lower crust and non-survival of some facies in hostile host magmas, and the lack of dimensional relations with surrounding lithologies, some interesting conclusions have emerged. For example, it is fair to say that one of the major conclusions of xenolith studies based on materials from southern Africa, the Colorado Plateau, northern Mexico, the Massif Central and eastern Australia is that the lower crust is predominantly mafic in character with polygenetic origins but predominantly of assimilation-modified under- and intraplated basaltic magmas and cumulates derived therefrom. As an example of the different conclusions that might be drawn from studies of Grenville-age outcrops and deep-seated xenoliths (entrained in Tertiary basalts) in Mexico, Ruiz et al. (1987)(1) have shown that the exposed granulites are on average of andesitic compostion (63 wt% SiO_2), whereas the xenoliths are significantly more mafic (average 53 wt% SiO_2).

There are however, difficulties in the way of accepting the hypothesis that the lower continental crust is everywhere mafic in character. Although petrologic and geophysical evidence for a mafic lower crust are satisfyingly in accord in the case of eastern Australia (2) (thermobarometry, crustal velocity structure, lack of Moho), the same is not everywhere true. While increasingly there is recognition that the Moho is not necessarily a simple ultramafic/intermediate rock contact, the persistence of rapid changes in seismic wave velocity at the base of the crust is incompatible with the presence of thick sequences of mafic materials in granulite-eclogite facies.

In more general terms, our models of crustal formation which depend heavily on the modern plate tectonic cycle are also in trouble. Despite occasional opinions expressed to the contrary, there is a consensus amongst petrologists actively engaged in the study of island arc magma genesis that the primary flux of material to the arc crust is basaltic in character. This flux may be expressed as intermediate to silicic eruptives in some arcs, expecially those constructed on pre-existing continental crust, but the point remains that modern-day crustal growth in arcs appears to involve basalt as the prime building block.

The granite extraction cycle can of course operate on this building block without the same volumetric lever that would exist in the case of an intermediate composition protolith. The major difficulties with this type of model are 1) the creation of an embarassingly large mafic-ultramafic restite that has not been recognized petrologically, but may not be distinguishable seismically from peridotite in the upper mantle; 2) the necessity of general disposal of this restite at least from the crust given the lack of evidence for its residence at the base of the crust.

It might be argued that present-day arc petrogenesis is not directly relevant to the problem of the major periods of Archean and Proterozoic crustal growth. For example, higher temperatures gnerally prevailing in subduction zones might have permitted the direct anatexis of hydrated ocean floor (solidus at about 800°C in the pressure range 5 - 25 kbar) rather than the devolatilization inferred at present. Two points should be made with respect to this model of direct silicic magma production in the Archean: a) the products of wet melting of basalt are not like "calcalkalic" series; b) the pervasive invasion of peridotite overlying the subducted lithosphere by melts of elevated Si/Mg ratios should surely have raised this ratio in upper mantle peridotite above chondritic, whereas the observed ratio is less than chondritic and thereby a major constraint on models of mantle formation.

It is clear that major problems persist with our detailed understanding of continental crustal growth, and that uniformitarianism may not be a helpful concept in the resolution of the difficulties.

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30 ANORTHOSITES: CLASSIFICATION, MYTHOLOGY, TRIVIA, AND A SIMPLE UNIFIED THEORY

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Ashwal and Burke (1) offered a provisional classification of anorthosite, which is given here in Table 1 along with the general characteristics of each type. I use this as a basis to discuss and dispel certain misconceptions about anorthosites. I also include here in Table 2 some interesting facts about terrestrial anorthosites for those interested in world records.

Myth #1. There was a distinct anorthosite "event" in the late Proterozoic.

Terrestrial anorthosites are commonly perceived as uniquely Precambrian rocks which formed during a catastrophic anorthosite "event" about one billion years ago (2). This myth probably owes its origin to the fact that in the Grenville Province of the Canadian Shield, a terrane unusually rich in anorthosite, many (but certainly not all) of the massifs have been strongly deformed and metamorphosed by the intense late Proterozoic Grenvillian orogeny, a probable Tibetan-style continent-continent collision. The Grenvillian event effectively reset isotopic systems including K-Ar, Rb-Sr, U-Pb, and even to some extent Sm-Nd. There has been some success, however, particularly with the whole-rock Sm-Nd method, in revealing pre-metamorphic ages (3). It is clear that even highly deformed massifs such as in the Adirondacks, N.Y. pre-date the Grenvillian event, and if the interpretation of Ashwal and Wooden (3) is correct, as much as 300 Ma may separate emplacement of the Marcy anorthosite massif and the younger metamorphism. In any case, reliable ages of anorthosite massifs in the eastern Canadian Shield range between about 1.1 and 1.65 Ga (4,5), and possibly as old as 2.55 Ga, if the River Valley anorthositic pluton of the southwestern Grenville Province (6) is considered a true massif. There is no evidence, therefore, for a distinct anorthosite event. Massif-type anorthosites do seem to be, however, a strictly Proterozoic phenomenon, and a satisfactory explanation for this is as yet unavailable. If other anorthosite types are included, it may be stated that anorthosite has been produced over the entire range of geologic time, and is forming today (Table 1).

Myth #2. Anorthosites are a major constituent of the lower crust.

There has been and continues to be, in the minds of many, an unfair connection between anorthosites and granulite facies metamorphism. Perhaps this is because the better known, or more easily accessible occurrences have been punished this badly. In addition, or possibly as a result, a popular hypothesis for the origin of massif-type anorthosites invloved intrusion, crystallization, and cooling of the massifs in the lower crust (e.g. 7). Decades of work in the relatively inaccessible parts of Labrador by E.P. Wheeler and S.A. Morse and their colleagues show that the voluminous anorthosites of the Nain Province were emplaced into the upper crust, at depths no more than about 5 km (8,9). More recently it has been shown on the basis of oxygen isotopic measurements that the Adirondack anorthosite, although metamorphosed to high pressure granulite facies, was originally emplaced at a shallow level, probably less than 10 km depth (10). Although deep emplacement of anorthosite is a possibility in some cases, these appear to be the exception rather than the rule.

A related myth holds that anorthosite can form as a refractory residue during anatectic melting within the crust. There is some support for this hypothesis from high pressure experimental petrology (11), and the idea of residual anorthosite after extraction of broadly granitic melts from the deep crust has been incorporated into some widely accepted tectonic models of Tibetan-style continental collision zones (e.g. 12). There is no convincing evidence that ANY known anorthosite formed in this way. Rather, anorthosites are plutonic igneous rocks which crystallized from mantle-derived silicate magmas.

Several authors have speculated that anorthosite should be a substantial (12,13), if not a major (11,14) constituent of the lower continental crust. Seismic studies (15) permit, but do not prove this. Admittedly, some deep crustal terranes exposed at the surface do contain anorthosite (e.g. Adirondacks,West Greenland, South India), but as discussed above, this is a vagary of collisional tectonics. Many high-grade terranes, such as New Quebec (16) are anorthosite-free. The relative paucity of anorthosite among lower crustal nodule suites of kimberlites and alkali basalts also argues against an anorthositic lower crust. There is no reason, therefore, to suspect that anorthosite is any more abundant in the lower crust than it is on the Earth's surface.

Myth #3. Archean anorthosites are metamorphosed equivalents of layered mafic intrusions.

A variety of origins have been proposed for Archean calcic anorthosites (summarized in ref. 17). One popular notion, based primarily on the Fiskenaesset anorthosite of West Greenland, and subsequently extended to other occurrences, is that these anorthosites represent metamorphosed and deformed equivalents of anorthosite-bearing layered intrusions ("stratiform type") such as the Bushveld or Stillwater (18). The differences among these two anorthosite types far outweigh their similarities. Archean anorthosites are characterized by a distinctive texture consisting of equant, calcic plagioclase megacrysts in a mafic groundmass which is commonly basaltic in composition. This texture can be recognized in nearly all Archean anorthosite occurrences, even in those affected by high grade metamorphism (e.g. 19), and is absent from anorthosite-bearing layered intrusions. Although there is some overlap in plagioclase composition between the two anorthosite types, Archean anorthosites are uniformly highly calcic (Table 1). In contrast to Archean anorthosites, layered mafic intrusions are not temporally restricted (Table 1). The tectonic setting of Archean anorthosites is still poorly understood, but many are associated with mafic volcanic units of greenstone belts, suggesting the probability of an oceanic setting (20,21).

A Simple Unified Theory

Basalt is a mantle-derived partial melt of peridotite. A similar fundamental statement about the origin of anorthosite cannot be made with equal certainty. Anorthositologists cannot yet agree as to whether the parental melts of anorthositic rocks were crustal- or mantle-derived, let alone what the composition of these melts was. I believe, however, that sufficient geological, petrological, mineralogical, geochemical, and isotopic information exists about anorthosites of all types to make a general statement concerning their origin: "anorthosites are cumulates of plagioclase feldspar from mantle-derived basaltic magmas." I offer this simple statement as a provisional hypothesis applicable to <u>all</u> anorthosite types, both terrestrial and extraterrestrial.

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Table 1. Anorthosite Types and Characteristics

Type	Texture	mol.% An	Ages (Ga)	Ore Deposits	Examples
Archean	equant megacrysts up to 30 cm	75–90	2.7–3.75	Cr, Fe-Ti	Bad Vermilion L, Ont; Sittampundi, India
Proterozoic (Massif-Type)	laths up to 1 m	40–65	1.0–1.7+	Fe-Ti	Marcy, N.Y.; Nain, Labrador
Stratiform	variable	50–80	0.1–2.7	Cr, Pt, Fe-Ti, V	Stillwater, Montana; Dufek, Antarctica
Oceanic (a) mid-ocean ridge	adcumulate	68–75	0.0	—	mid-Atlantic, mid-Indian ridges
(b) ophiolite	adcumulate	78–82	0.44–0.04	—	Bay of Islands, Newfoundland
Inclusions (a) cognate	variable	variable	0.0–1.2	—	Gardar dikes, Greenland
(b) xenolithic	variable	variable	?	—	Beaver Bay diabase, Minnesota
Extraterrestrial	adcumulate	95–98	~4.4	?	Lunar crust

Table 2. Anorthosite Trivia

Oldest:	3.75 Ga Manfred Complex, Yilgarn Block, Western Australia
Youngest:	0.00 Ga Mid-Atlantic, Mid-Indian, Mid-Cayman Ridges
Largest:	> 15,000 km^2 Cunene massif, Angola
Most Punished:	Sittampundi anorthosite (Archean), India (plag > cor + liq)
Most Profitable:	Bushveld Layered Intrusion, South Africa (Pt, Cr, Fe, Ti, V)

GEOCHEMISTRY OF AMPHIBOLITES FROM THE KOLAR SCHIST BELT;
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Amphibolites are the predominant rock type of the Kolar Schist Belt. Because the amphibolites are interbedded with ferruginous cherts and graphitic schists and show rare pillow structures, it is thought that they originally formed in a submarine environment. The amphibolites are komatiitic and tholeiitic in composition. The komatiitic amphibolites are relatively minor and occur as thin, folded units interbedded with the tholeiitic amphibolites near the eastern and western margins of the belt. In the central part of the belt is a fine-grained, massive, tholeiitic amphibolite, which divides the belt into western and eastern parts. The komatiitic amphibolites to the east have Ce/Nd ratios graeter than that of chondrites, while those to the west have Ce/Nd ratios less than that of chondrites (Fig. 1). Rajamani et al. (1,2) suggest: that the komatiitic amphibolites are derived by relatively low percentages of melting (less than about 20%) of a mantle source with a somewhat higher Mg/Fe ratio than pyrolite at pressures of about 50 Kb; and that the tholeiitic amphibolites are not simply related to the komatiites, but are derived from a source with a much greater Fe/Mg ratio than that of the komatiites at pressures less than about 25 Kb.

The komatiitic amphibolites from the western side of the belt have a wide range in Sm/Nd ratios, which we interpret as reflecting varying proportions of garnet left in a residue as a result of different extents of melting (Fig. 2). The Sm/Nd age for the western komatiitic amphibolites is 2690 ± 140 Ma with epsilon Nd values ranging from +2 to +8. No known rock can act as a contaminant to produce these high, positive epsilon values. Thus, we suggest that the sources of these rocks were (variably?) depleted in light REE for a significant period of time. We have to wonder whether these western komatiitic amphibolites may be Archean representatives of modern mid-ocean ridge basalts. The eastern komatiitic amphibolites have a restricted range in Sm/Nd so that no age is calculable. They have an epsilon Nd of +2 to +7 at 2690 Ma.

The eastern komatiites, western komatiites and western tholeiites all have quite different U-Pb histories (Fig. 3). The scatter in the Pb isotope whole-rock data for each of the types of amphibolites suggests that the amphibolites may have been contaminated by extraneous Pb, perhaps from the surrounding gneisses. The Pb data from one outcrop of the central massive tholeiitic amphibolite give a Pb-Pb isochron age of 2733 ± 155 Ma, which is consistent with the Sm/Nd isochron age for the western komatiites. Surprisingly, the Pb data for the komatiites and tholeiites are quite different, suggesting the interlayered komatiites and tholeiites have separate sources. Less surprisingly, the eastern komatiitic amphibolites have Pb isotope characteristics quite different from those of either the western komatiites or western tholeiites. Too few eastern tholeiitic amphibolites have been analyzed to determine whether they also have separate sources.

Fig. 1. Ce versus Nd concentrations of the western and eastern komatiitic amphibolites compared to a line with a chondritic Ce/Nd ratio. Essentially all of the western komatiites have a Ce/Nd ratio less than that of chondrites, whereas the eastern komatiites have a Ce/Nd ratio greater than that of chondrites. This consistent difference in ratio over a large range in composition implies that the mantle sources for the two komatiitic suites had the same Ce/Nd characteristics as the amphibolites (3).

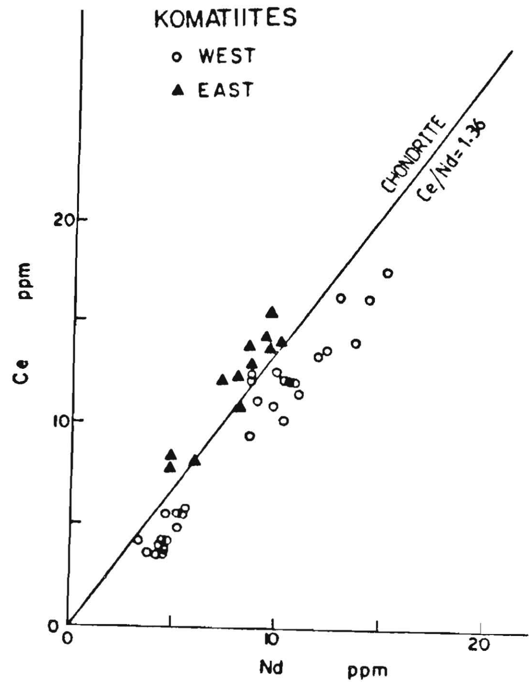
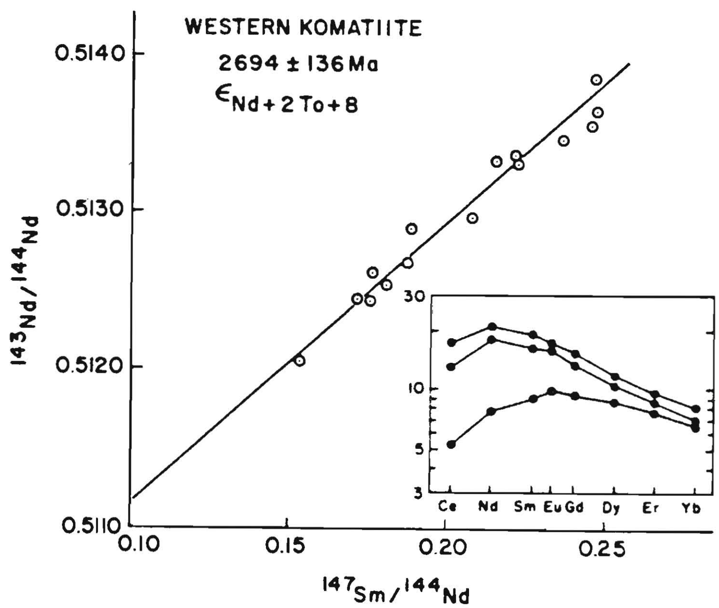


Fig. 2. Sm/Nd isochron diagram for samples of the western komatiites. The inset shows REE patterns for representative samples of this suite. The spread in Sm/Nd ratios is most probably due to varying extents of melting of a mantle source leaving varying fractions of garnet in the residue. The Sm/Nd isochron would thus be dating the time of melting. The positive epsilon values and scatter of data suggest a source for the western komatiitic amphibolites with a long-lived history of variable, light REE depletion.



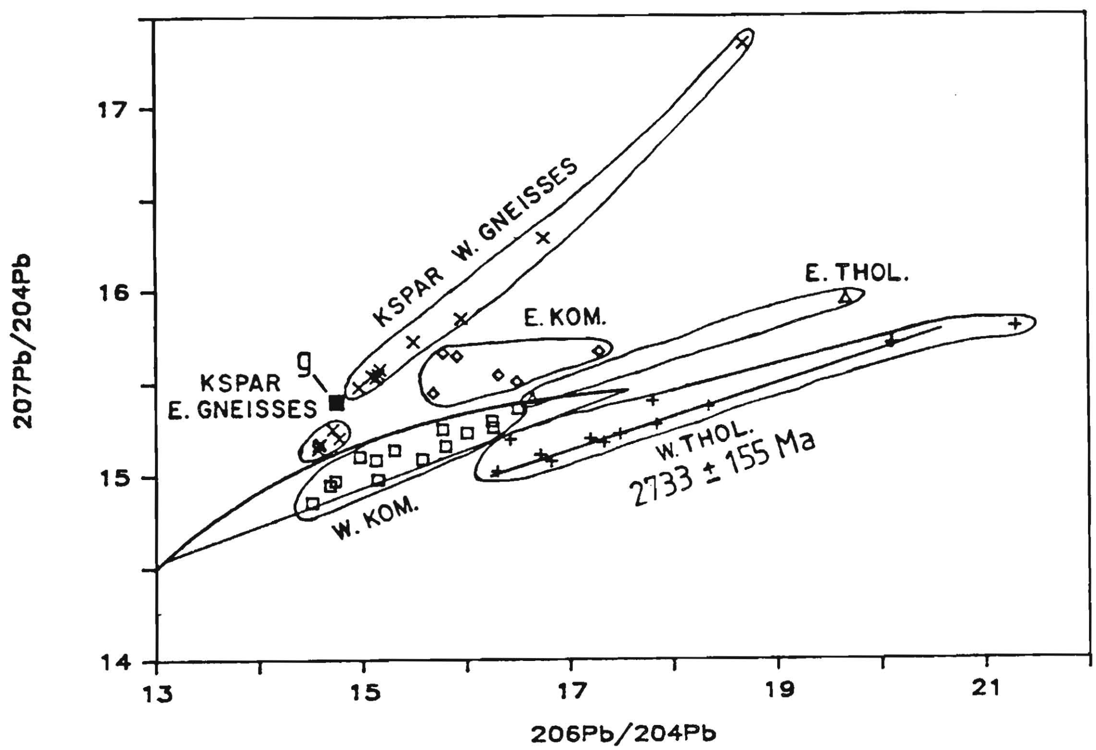


Fig. 3. Pb isotope data for the eastern and western komatiitic and tholeiitic amphibolites compared to the Pb isotope data for leached potassium feldspars from the gneisses east and west of the belt (4) and galena from within the belt (5). Whereas the Pb data for the western tholeiitic amphibolites from a number of outcrops show a scatter, the data for samples from one outcrop lie closely about a line and give an age of 2733±155 Ma. The Pb isotope data for the eastern and western komatiites show considerable scatter, suggesting that they may have been contaminated by extraneous Pb, perhaps represented by the galena which has a composition similar to that of some of the western gneisses.

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NATURE OF THE COAST BATHOLITH, SOUTHEASTERN ALASKA: ARE THERE ARCHEAN ANALOGS??

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Two geochemical and geochronological traverses across the 1,760-km-long and 50-150 km-wide continental margin Coast batholith (Coast Plutonic Complex in Canadian nomenclature), of southeastern Alaska and British Columbia at Skagway and Ketchikan-to-Hyder show:

(a) episodic intrusion at ca. 127Ma, 57-55Ma, 54-52Ma, 48 Ma and 32-19Ma (a minor, postsubduction event) of

(b) transversely localized and longitudinally extensive rock suites,

(c) each of which consists of part of the calcalkaline trend hornblende-biotite diorite-quartz diorite-tonalite-quartz monzodiorite-granodiorite-granite (IUGS terminology): gneissic diorite to tonalite at 127Ma, quartz diorite and tonalite at 57-55Ma, tonalite and granodiorite at 54Ma, granodiorite and granite at 54-52 Ma, granite at 48Ma and gabbro and granite at 32-19Ma; distributed so that

(d) the western part of the batholith is largely diorite to tonalite and the eastern part tonalite to granite.

All rocks show high concentrations of Sr and Ba, medium to high K and moderate light REE enrichment with small or no Eu anomalies. $^{87}Sr/^{86}Sr_i$ ratios of 0.7047-0.7066 show mild decrease with age and a larger range at higher SiO_2 contents. Five $^{143}Nd/^{144}Nd_i$ ratios are 0.51229-0.51264 and are of island-arc or immature-crustal values. Compositions at SiO_2 of ca. 55-63% are like those of Gill's average medium-K and high-K orogenic andesites. Pillowform inclusions of high-Al basalt are found in several suites and represent coeval magma derived from the underlying subduction zone.

Just west of Coast batholith, as in the region east and north of Ketchikan, intrusives of quartz diorite and tonalite are found. These are 93-89Ma old, chemically resemble Coast batholithic rocks, but show lower $^{87}Sr/^{86}Sr_i$ ratios (0.7041-0.7049), generally higher $^{143}Nd/^{144}Nd_i$ ratios (0.51246-0.51265) and lower K. These plutons may not have been emplaced in their present positions (relative to Coast batholith), but their chemical character indicates origin above a subduction zone.

Coast batholith not only formed in direct response to subduction of Pacific plates, but it is wholly bounded by accreted terranes of oceanic or slope origin. Unlike Sierra Nevada, Idaho and Peninsula Ranges batholiths, Coast batholith formed hundreds of kilometers from Precambrian crustal rocks. Its compositional trend is probably in large part a result of damp fractionation of gabbroic or dioritic magmas, with the exception that the granites may contain large crustal components.

Are analogs of Coast batholith found in the Archean? Like many Archean plutonic suites, Coast batholith formed in relatively young volcanic and sedimentary rocks. However, the abundant rocks of intermediate SiO_2 content of the western half of the batholith are not common in the Archean, whereas the abundant trondhjemitic plutons of the Archean are rare to absent in Coast batholith (except as seams formed by in-place melting of metabasalt inliers). The granites and granodiorites of Coast batholith tend to be less radiogenic than its quartz diorite and tonalite, in opposition to typical Archean occurrences. The answer, perhaps, is "no". Archean plate-tectonic processes, in producing evolved magmas different from those of Phanerozoic subduction zones, probably were unique.

HOW WIDELY IS THE ANDEAN TYPE OF CONTINENTAL MARGIN REPRESENTED IN THE ARCHEAN? Kevin Burke, Lunar and Planetary Institute, 3303 Nasa Road One, Houston, TX 77058 and Department of Geosciences, University of Houston, University Park, Houston, TX 77004

Continents are elevated above the ocean floor because continental crusts are made up of material lighter than the overwhelmingly basaltic oceanic crust. The great bulk of igneous rocks less dense than basalt forming today is made at convergent plate boundaries and for this reason processes at convergent boundaries are considered most likely to have been dominant in the production of the continental crust.

Convergent plate boundaries can be characterized as: Island arcs, Andean Margins and Collision zones (both arc-continent collision zones and continent-continent collision zones). Only island-arc convergent boundaries can originate entirely within the ocean (perhaps nucleating on oceanic fracture zones) and for this reason this type of boundary is likely to have been involved in forming the world's first "continental crust" at more than 4 Ga. Compositions of rocks formed at island arc boundaries in the Late Phanerozoic (for example, the Greater Antillean Island Arc [1] show close resemblances to some Archean rocks and it seems likely that this kind of material is widely represented within the Archean although some differences in source magmas and in proportions of rock types have been suggested.

Andean and collisional convergent boundaries are likely to involve (1) contamination of material newly-derived from the mantle by material already in the continental crust and (2) partial melting of that crust. These processes produce recognizable geochemical signatures (e.g. high initial strontium isotopic ratios) which are widespread among Archean rocks.

It therefore seems possible that Andean margins and both kinds of collisional boundaries are represented within the Archean and I here draw attention to a simple structural criterion that may be applied to discriminate between Andean margins and continental collision zones. Continental collision zones are enormous in area (10^6 km^2) (e.g. Tibet today) and have been so in the past, (e.g. the Grenville Province and the Pan African). It is hard to recognize such huge areas among Archean rocks because of the limited extent of most preserved Archean provinces, but the 0.5×10^6 km^2 area of granulite within the Superior Province of Labrador is the most likely candidate. By contrast, Andean margins are long ($\sim 10^3$km) and narrow (as the Andes today) and volcanism within Andean provinces is usually restricted to a narrow zone less than 100 km wide expanding to a broader area (such as in South America today) only in areas of extreme shortening of the basement [2].

The Phanerozoic history of the Andes shows that apart from rafting in of arc and microcontinental material ("terranes" of some authors) which was important in the Paleozoic in the South [3] and has been important again within the last 100 Ma in the North [1], there have been episodes of crestal rifting [4] and marginal basin formation [5] within the Andean arc. Possible analogues of these features are common in the Archean record (e.g. 6).

In summary: Andean margins are likely to be recognized in the Archean as: (1) the site of abundant granodioritic to granitic intrusions with either or both of mantle and older continental isotopic signatures, (2) occupying a length of hundreds of kilometers, but (3) only a width one or two hundred km, (4) cut by mafic dikes representing episodes of extension within the arc, (5) the site of crestal-rift volcanic rocks (like those of Taupo in New Zealand, e.g. [ref. 6] and, (6) the site of marginal basins (like the Rocas Verdes [5]).

ANDEAN ARCHEAN MARGINS?

Burke, K.

Although it is clear that no Archean Andean margins can have survived within continents, Andean margin remains have been recognized in the Superior Province of Canada [ref.7] and the Closepet "granite" of Southern India may represent another example. It seems possible that Andean margins may be rather widely represented among Archean rocks and that there are good possibilities of recognizing them on structural grounds, perhaps complimented by compositional evidence. It seems clear that compositional evidence alone will always be ambiguous because it cannot distinguish Andean from collisional environments [pace, ref. 8].

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Water Activities in the Kerala Khondalite Belt

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The determination of $a(H_2O)$ and $a(H_2O)$ gradients in granulite terrains can provide important constraints on their petrogenesis[1,2,3]. In this study, we calculate $a(H_2O)$ in various rock types of the Kerala Khondalite Belt (KKB) and evaluate the granulite-facies metamorphism of the region in light of this information.

Two of the major rock types of the KKB contain mineral assemblages that permit the characterization of $a(H_2O)$. The charnockites contain bt + qtz + opx + kfs + (grt-ilm±gr) and the khondalites contain bt + qtz + sil + grt + kfs ± (crd-spl-ilm-gr). These two assemblages define the equilibria: (R1) 2 Phl + 6 Qtz = 3 En + 2 Kfs + 2 H_2O and (R2) Phl + 2 Qtz + Sil = Prp+ Kfs + H_2O, respectively, and can be used to calculate $a(H_2O)$, provided that pressure and temperature are known and the relevant thermodynamic data and activity-composition models are available.

Geothermobarometric studies [4] indicate that the entire KKB was metamorphosed at relatively uniform conditions of 5.5 kb and 750°C. Therefore, all calculations were made at this pressure and temperature. The position of the Mg-end-member reactions were calculated using thermodynamic data from the internally consistent data set of Holland and Powell [5]. It is possible to make the calculated positon of R1 agree with the experimental bracket of Bohlen et al. [6] at 5 kb and $X(H_2O)$= 0.35 by adjusting the thermodynamic values of Phl [7]. Because recent calorimetric measurements [8] suggest that the $\Delta H^f_{Phl,298}$ listed in Holland and Powell [5] is correct, we have chosen to increment the $S°_{Phl,298}$ until the calculated position of R1 agrees with the experimental bracket. The shallower slope of R1 calculated with this larger $S°_{Phl,298}$ is in better agreement with the slope of R1 (at $X[H_2O]$ = 1) determined by Wood [9].

a_{Phl}^{Mica} and a_{En}^{Opx} were calculated using ideal on-sites mixing models [10,11]. The a_{Kfs}^{Afs} was assumed to equal X_{Kfs}^{Afs}, where X_{Kfs}^{Afs} was determined from the composition of coexisting plagioclase at 750°C according to the model of Stormer [12]. The a_{Prp}^{Grt} was calculated using the model of Newton et al.[13].

The results of the calculations are shown in map-form in Fig. 1. The charnockites give an average $a(H_2O)=0.27\pm0.05$ (1σ) and the khondalites an $a(H_2O)=0.26\pm0.06$ (1σ). The striking feature is the uniformly low $a(H_2O)$ recorded over a large region. This uniformity is in marked contrast to a number of other granulite terrains where significant gradients in $a(H_2O)$ have been documented over a kilometer or even a meter scale [2,3].

Two lines evidence suggest the uniform $a(H_2O)$ of the KKB rocks were not caused by the extraction of a partial melt. First, within each rock type, $a(H_2O)$ shows no obvious correlation to bulk compostional variables such as silica content, Fe/Mg ratio or $a(TiO_2)$. Thus, "restite-rich" assemblages record approximately the same $a(H_2O)$ as more leucocratic assemblages. Second, there is a remarkably good agreement between $a(H_2O)$ in the charnockites and khondalites. If this agreement is correct then it would seem highly fortuitous that two contrasting rock types, which encountered different melting reactions, partially melted to yield identical $a(H_2O)$.

The simplest interpretation of the $a(H_2O)$ data is that the rocks of the KKB equilibrated with a low $a(H_2O)$ fluid that had a roughly constant composition throughout the region. The patchy replacement of garnet-biotite gneiss by coarse-grained charnockite along deformation zones and foliation planes provides field evidence for this fluid-present metamorphism [14,15]. It is the opinion of the authors that the low $a(H_2O)$, presumably CO_2-rich, fluids were introduced from deeper levels. However, a model invoking internally-derived fluids, such as those generated by the reaction bt + qtz + gr = opx + kfs + v [16], possibly under conditions of $P_{fluid} < P_{lithostatic}$ [14], would also be consistent with the $a(H_2O)$ data, provided that these fluids were sufficiently water-poor.

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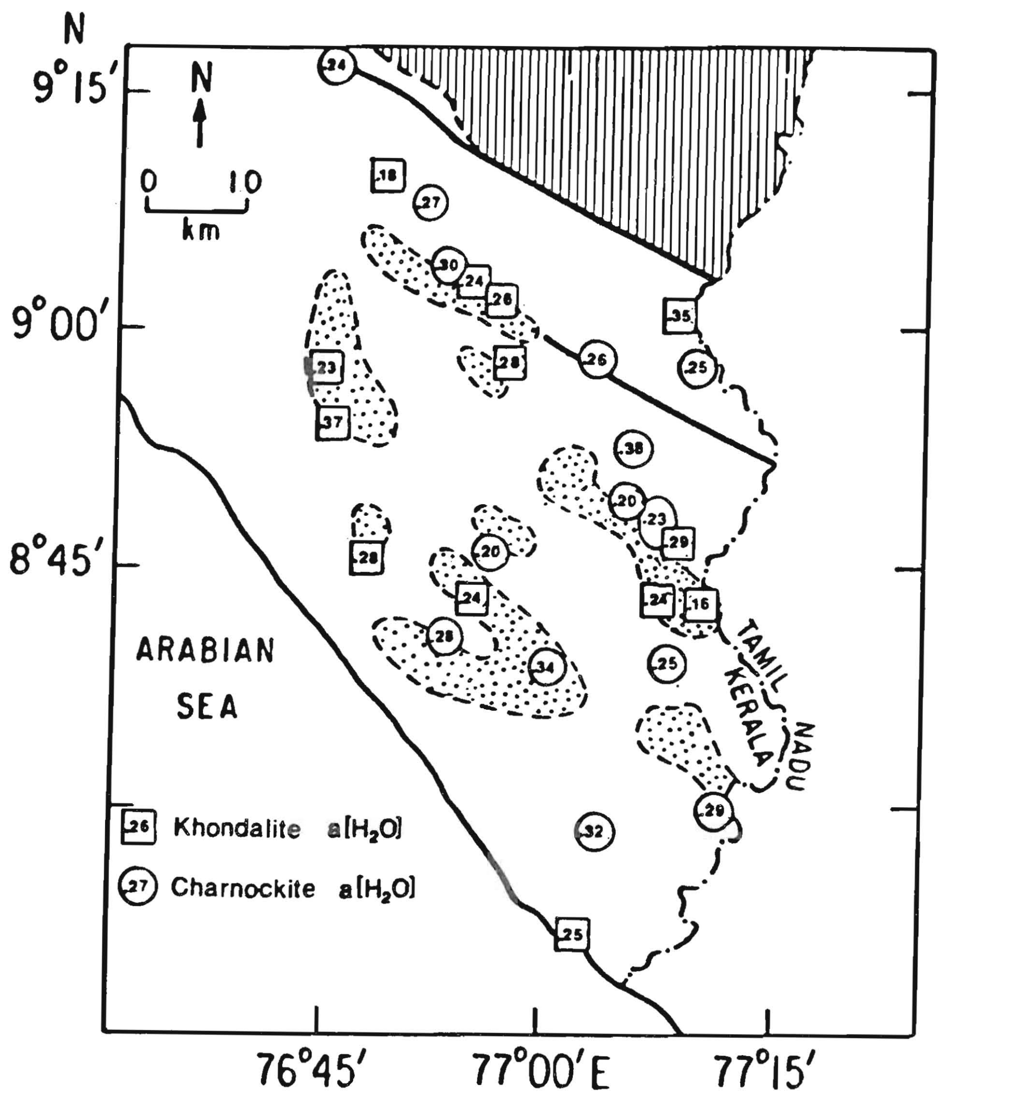

Fig. 1. Calculated $a(H_2O)$ values in charnockites (circles) and khondalites (squares) of the Kerala Khondalite Belt.

METASEDIMENTS OF THE DEEP CRUSTAL SECTION OF SOUTHERN KARNATAKA.

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The deep continental crust all the world over includes within it a close association of charnockitic granulites and metasediments. Noting the constant association of the two in the deep crustal charnockite region of southern peninsular India, Naidu (1) remarked "A 'charnockite province'........ is mainly psychological. It can as well be a 'khondalitic' or 'calc-silicate' province."

The southern Karnataka region discussed here (longitude 77° 7' - 77° 15' E and latitude 12° 13' - 12° 40' N) constitutes the northern fringes of the charnockite region. While the northern part of over 1300 sq.km. is composed essentially of amphibolite facies gneisses and granites, the southern about 600 sq.km. exposes granulites and transition granulite amphibolite facies rocks. The metasediments occur all over the area as small isolated enclaves and as conformable bands, lenses, pods and patches. Both metasediments and the associated charnockites and the amphibolite facies gneisses are tightly (and repeatedly) folded/deformed together. The correct stratigraphic sequence among the different metasedimentary units is not revealed by the recorded pattern of their distribution. Neither is the age relation between the metasediments and the charnockites inferrable. Quite strikingly whether enclosed within the granulite or the amphibolite facies rocks, the metasediments display about the same degree of granulite facies metamorphism and there is not much of later retrograde metamorphic impress.

The metasediments of the area could be broadly divided as siliceous, aluminous, Fe-Mn and impure calcareous types. The siliceous sediments vary from pure ortho-quartzites to those corresponding to shaly (and ferruginous) sandstones containing small proportions of sillimanite, cordierite, feldspars, mica, pyroxenes and garnet which tend to be concentrated in occasion thin laminae. The aluminous sediments vary from garnetiferous (+ pyroxenes) quartzofeldspathic rocks (i.e., corresponding to leptynites) and sillimanite quartzites to those containing a large proportion of cordierite (with consistently positive optic sign), sillimanite, almandine garnet (with 25 to 35% pyr) and biotite, and commonly including within them thin bands, patches and lenses of cordierite-orthopyroxene (with 3.5 to 4.5% Al_2O_3)-biotite and quartz-orthopyroxene-clinopyroxene-garnet (63% Alm 15% Pyr, 15% grs)-plagioclase (72-78% An) (+ hornblende) bearing units (Devaraju and Sadashivaiah) (2,3). The Fe-Mn sediments include banded Mn-poor (av 0.63% MnO) and manganiferous (av 7.6% MnO) iron-formations which occur completely mixed together and very commonly contain Fe-Mn pyroxenes (Opx with less than 0.4 to 15% MnO, Cpx with 0.1 to 7.5% MnO) and garnets (81.6 to 28% Alm and 3.6 to 49.6% spes) as major mineral phases (Devaraju and Laajoki) (4). The impure carbonate units typically occur as small isolated bodies usually containing ferrosalite (~55% He), Quartz, bytownite (72-78% An), grossularite (~67% gros), scapolite (~84% Me), carbonate and sphene (Devaraju and Sadashivaiah)(5). The mineral assemblages and mineral compositions of metasediments are distinctly different from those of the charnockitic granulites (while all the metasediments very commonly and typically contain garnet, the charnockites and also the amphibolite facies gneisses are generally devoid of garnet) and no significant mineralogical gradations are recorded between the two (exceptions are perhaps the noritic assemblages occuring at the contacts of pelitic units). The mineral assemblages of metasediments whether enclosed in charnockites or in gneisses are in textural/chemical equilibrium.

Both interms of major as well as trace element geochemistry, as distinct from charnockites and amphibolite facies gneisses, which are just about the same as calc-alkaline igneous rocks, the metasediments closely compare with those of common sedimentary rocks. Apparently, despite high-grade (and repeated) metamorphism, there was no significant migration of chemical constituents across the primary banding/lamination/stratification to obliterate the original sedimentary structures and the metamorphic reactions were remarkedly confined to the component units of individual sedimentary bands.

On the whole the sediments of the deep crust of Karnataka include clastic dominated siliceous to pelitic units, deposited in relatively shallow waters, and mixed clastic, volcanogenic to chemogenic impure calcareous to Fe-Mn units deposited in relatively deep waters. The manganiferous iron formations in particular, with a distinctly high average total of 15% Al_2O_3 + MgO + CaO, seem to represent an admixture of (volcano) clastic and chemical sediments. Like sediments in the Sargur sequence (Janardhan et al) (6) these also appear to have deposited in essentially shallow basins at the continental margins.

METASEDIMENTS OF THE DEEP CRUST

T.C. Devaraju, K. Laajoki and B.K. Wodeyar

Metamorphic temperature of 609° to 935°C (mean 673°C) and pressure of 6.5 to 10.7 kbar (mean 8.6 kbar) have been obtained for the metasediments according to the methods of Wood and Banno (7), Raheim and Green (8), Wells (9), Thompson (10), Ellis and Green (11), Ganguly (12), Kretz (13), Harley (14), Sen and Bhattacharya (15), Wood (16) and Ghent (17), Perkin and Newton (18). These data are similar to those obtained for the associated charnockites and are consistent with the observation that the two groups of granulite facies rocks are coeval and have had much the same metamorphic history (Devaraju and Sadashivaiah) (19). The geobarometric data obtained further suggests that the deep continental section exposed in southern Karnataka was at depths of about 30 kms at the time of granulite facies metamorphism.

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SIGNIFICANCE OF THE LATE ARCHAEAN GRANULITE FACIES TERRAIN BOUNDARIES, SOUTHERN WEST GREENLAND; **C. R. L. Friend**, Dept. of Geology, Oxford Polytechnic, Oxford OX3 0BP, U.K.; **A. P. Nutman**, Dept. of Earth Sciences, MUN, St. John's Newfoundland, Canada; and **V. R. McGregor**, Atammik, 3912 Sukkertoppen, Greenland, Denmark

Within a distance of c.60 km across the mouth of Godthåbsfjord (Fig. 1), three different Archaean granulite facies events are represented. First, that which affected the Amîtsoq gneisses at c.3600 Ma (1) is preserved only in relatively small areas. Second, that at c.3000 Ma affecting Nordlandet. Third, that at c.2800 Ma, which we discuss here, affecting the region south of the Qarliit nunaat thrust and south to Bjørnesund (Fig. 1).

This granulite facies event has been dated (Pb/Pb) at 2800±70 Ma (2) and at 2795± Ma (zircons) from an intrusive ferrodiorite/rapakivi (s.l.) granite suite (3). The block comprises probable middle Archaean gneisses, supracrustal rocks dominated by amphibolites and intrusive, layered gabbro/anorthosite complexes (see 4 for further references). Early deformation episodes culminated in granulite facies conditions, the assemblages of which were extensively retrogressed to amphibolite facies, frequently obliterating the early history, during the late Archaean. Two different boundaries, both now highly modified by the later events, have been recognised:

(a) Southern boundary

The boundary occurring in and around Bjørnesund (Fig. 1) have been variably retrogressed, but toward the head of the fjord is well-preserved and is shown to originally have been prograde. The boundary comprises the grey biotite ± hornblende and amphibolite-facies gneisses traversed by a network of brownish, orthopyroxene-bearing zones and cut by felsic, orthopyroxene-bearing pegmatite sheets. Orthopyroxene growth clearly overprints the amphibolite facies structures and fabrics on many scales. Owing to the proximity of granulite and amphibolite facies assemblages and the intricacy of the network, the relationship is interpreted as prograde and to have formed by fluid-dominated processes, similar to those in southern India (e.g. 5).

(b) Northern boundary

This is demonstrated to be a tectonic feature, the Qarliit nunaat thrust (Figs. 1 and 2) which was folded and metamorphosed in the late Archaean. This deformation decreases inland and the thrust becomes more apparent. South of the thrust granulite facies rocks are brownish weathering and toward the thrust relict brown cores surrounded by greyish-white, bleached rocks occur (Fig. 2). These bleached rocks have one or a combination of two fabrics within them. At higher structural and topographic levels new amphibolite facies minerals statically overprint and mimic the steeply dipping granulite facies fabrics. At lower levels the amphibolite facies minerals form a progressively more gently southerly dipping fabric sub-parallel with the thrust (Figs. 1 and 2). Generally, deeper structural levels (at 2800 Ma) are represented in this northern part of the block with preserved conditions of c. 10 kbar and 800°C (e.g. 6; our unpublished data).

DISCUSSION

Previous interpretations of the region are at variance with that presented here. The southern boundary was recognised to be prograde (7), but the patchy distribution of granulite assemblages in the Fiskenaesset region was interpreted to represent the original prograde boundaries which had been little modified by later retrogression (8). The northern boundary, despite detailed 1:20000 scale mapping, was also identified as prograde (6; 9). This misinterpretation is considered to be due to the interaction of the flat-lying foliation associated with the thrust and the steeply dipping foliation of the granulites during folding (Fig. 3). Additionally, PT data were assembled to represent PT conditions for synchronous amphibolite and granulite facies metamorphism (6) which is now known not to be the case. Recent data (10), the new data presented here and other unpublished results demonstrate that the granulite facies block evolved separately before being tectonically excavated and juxtaposed against lower grade rocks. Much of the granulite facies terrane, especially close to the thrust boundary, is dominated by the process of hydrous retrogression. Geochemical relationships in most of the northern part are thus considered to reflect *retrograde* rather than prograde processes. The use of the earlier interpretations to construct theories for the general evolution of continental crust (6, 9, 11) must be regarded with caution.

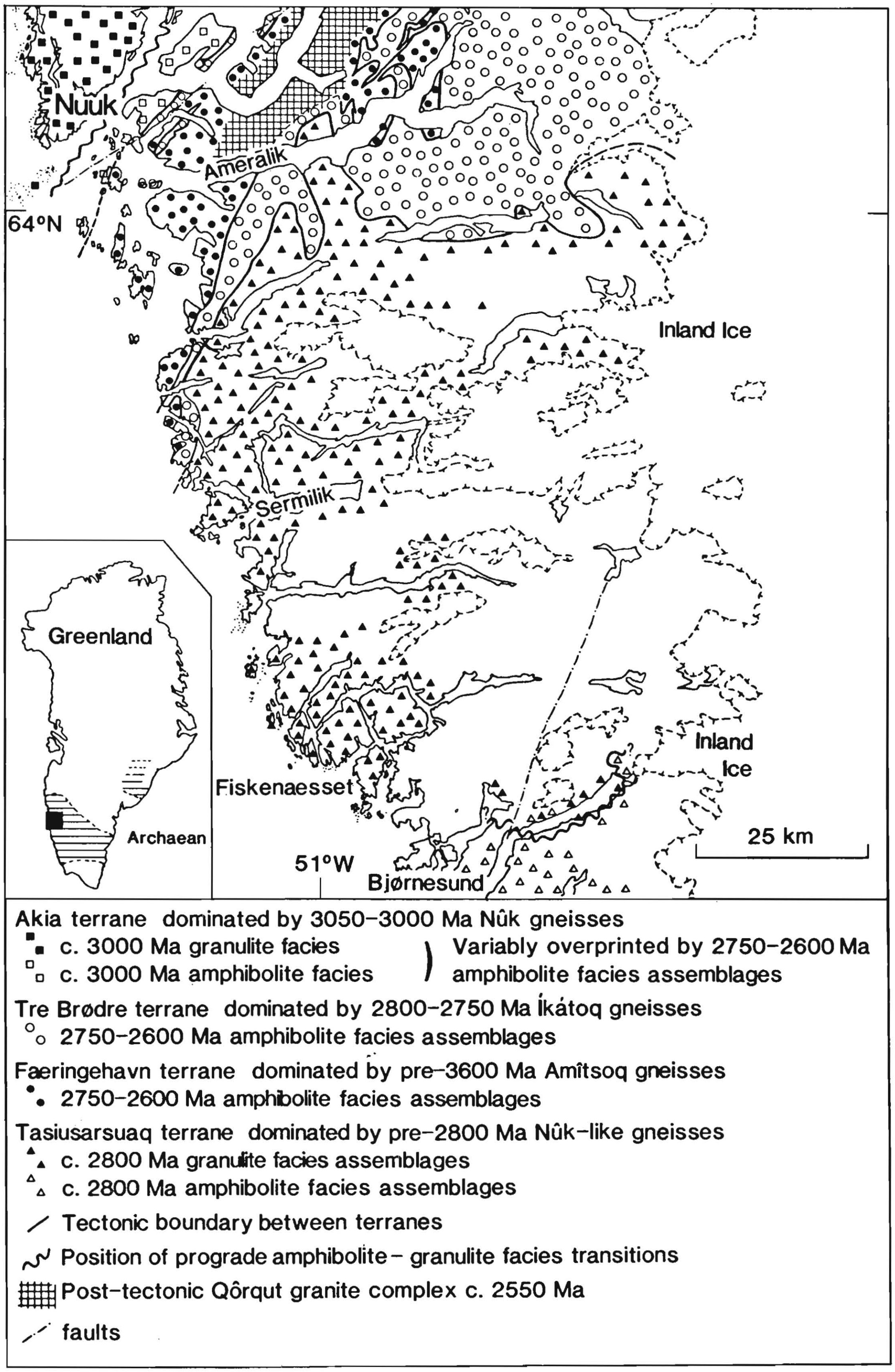

Fig. 1. Simplified sketch map of the Godthåbsfjord-Bjørnesund region showing the distribution of four distinct terranes and their boundaries as presently understood.

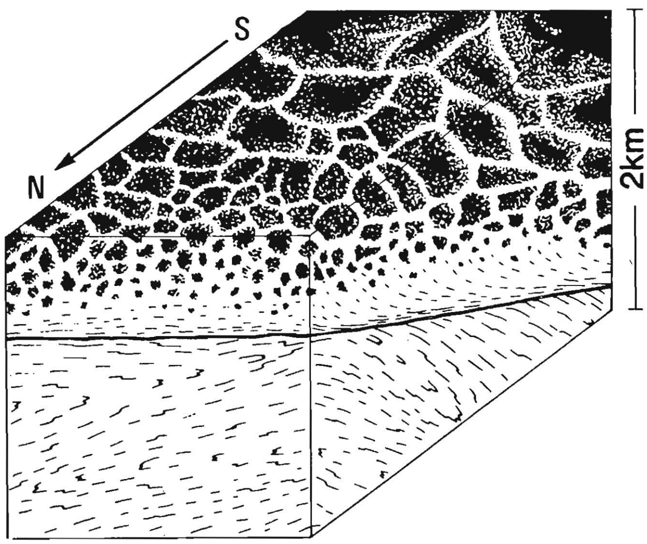

Fig. 2. Block diagram to show the topographical control over retrogression of granulite facies rocks above the Qarliit nunaat thrust. Unretrogressed (solid black) occurs at high structural levels associated with partially retrogressed rocks (heavy stipple). Statically retrogressed veins overprint the granulite fabric (white) and at lower levels a new amphibolite facies fabric is formed (white with dashes). Below the thrust amphibolite facies structures are deformed and are partially reoriented.

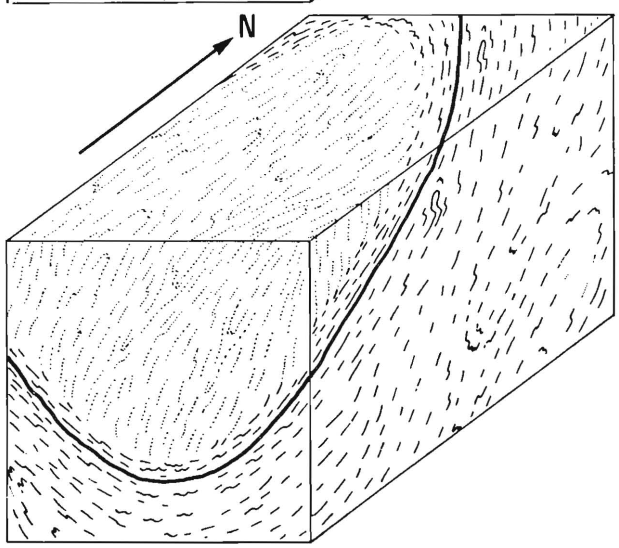

Fig. 3. Block diagram illustrating the effects of folding the thrust with its associated amphibolite facies fabric. The relatively competent granulites fold in a different manner to the flat-lying amphibolite facies fabrics.

Where there is more than one granulite facies event present, as for example now appears to be the case in southern India, it is important that each is carefully documented by a combination of associated field and laboratory studies, prior to amphibolite-granulite relations being used for crustal modelling.

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SIGNIFICANCE OF ELEVATED K/Rb RATIOS IN LOWER CRUSTAL ROCKS

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Lower crustal rocks with granulite mineralogies commonly have K/Rb ratios that are range up to 2000 (see field enclosed by dashed lines, Fig. 1), many times that found in most volcanic rocks. These high ratios have been interpreted by many authors as having been produced by massive influx of H_2O-poor fluids that preferentially removed Rb during breakdown of biotite and hornblende[1,2]. The same Rb depletion may also be produced by simple dehydration[3]. Consequently, high K/Rb ratios in granulite facies rocks are often used as evidence that the granulite metamorphism leads to extensive metamorphic differentiation of the lower crust[1,4-7]. It is our contention that high K/Rb ratios may form by igneous processes as well as from metamorphic ones and that the presence of granulites with high K/Rb ratios in no way implies that granulite metamorphism necessarily leads to depletion of rocks in LIL elements.

Granulitic rocks with high K/Rb ratios have one common characteristic: they also have less than 1.5% K_2O. Such low-potassium rocks rarely contain a separate potassium feldspar phase; the small amount of potassium present can be accommodated in plagioclase. For example, experimental results[8] indicate that a plagioclase with Ab/An = 0.70 can accommodate 2.3% K_2O at 825°C and 1 kilobar, and thermodynamic modelling[9] indicates that solubility of K_2O will increase in plagioclase with increasing pressure. Thus a granulite containing 70% plagioclase metamorphosed at 825°C can accommodate 1.7% K_2O in the plagioclase without contributions from any other phase.

Crucial to the understanding of Rb behavior during lower crustal igneous processes is the concept that a silicic magma emplaced under granulite conditions will not be able to cool to the H_2O-saturated solidus. Rather it would be expected to crystallize pyroxene-bearing cumulates while a more hydrous and evolved melt moves to higher crustal levels[10]. Thus many pyroxene-bearing rocks may be cumulates, rather than direct representatives of a melt. Although available Kd data for melt-crystal fractionation are highly variable, they do indicate that Rb is strongly incompatible with plagioclase, while K is more compatible[11]. Plagioclase phenocrysts from volcanic rocks have K/Rb ratios ranging from 440 to more than 4000, with the lower values found in more anorthitic plagioclase[12]. This indicates that a cumulate consisting of plagioclase and pyroxene, with or without quartz, forming from a melt with normal K/Rb can have K/Rb ratios as high as those found in granulite terranes (see ref. 13). In rocks where orthoclase is a crystallizing phase, however, Rb becomes far more compatible[14] and Rb depletion does not accompany formation of cumulates.

As can be seen in Figure 1, K/Rb ratios for unmetamorphosed, plagioclase-pyroxene cumulates, involving both anorthosites and dioritic rocks, from both the Laramie[15] and Nain Complexes[16] have precisely the same trends as seen in granulite terranes. In both the K/Rb ratio increases with decreasing K content. Furthermore, these indisputably igneous rocks also have the very low Rb/Sr ratios previously attributed to granulites[2]. It is evident, therefore, that rocks strongly depleted in LIL elements may form by cumulate processes as well as by metamorphic processes. Thus the depleted geochemical signature which is commonly distinctive of granulite facies provides no real constraint on the processes by which these rocks formed. Rather, detailed geologic mapping of each terrane is required to determine whether the geochemical signature is the result of igneous or metamorphic processes.

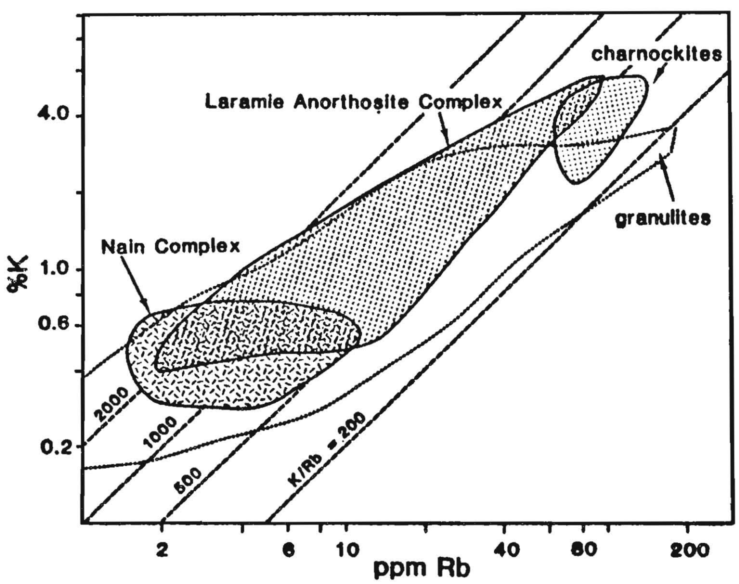

Figure 1: Comparison of K/Rb ratios for granulites (dashed line), charnockites, and cumulates from the Nain and Laramie anorthosite complexes. Data from 15 - 19.

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PRESENT STATUS OF THE GEOCHRONOLOGY OF THE EARLY PRECAMBRIAN OF SOUTH INDIA.

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Available geochronological data, though scanty, indicates that sialic crust in the form of tonalitic gneisses developed in south India 3.3 to 3.4 Ga ago. These early gneisses so far recognised only in a few parts of western Karnataka are mainly migmatites. However, there is as yet no clear geochronological evidence that these gneisses were preceded by a supracrustal cycle. Recognisable supracrustal belts appear to have evolved either within or bordering this sialic crustal block.

The exposed Archaean supracrustal rocks have been divided into an older sequence (the Sargur Group, older greenstone belts) and an younger voluminous sequence (the Dharwar Supergroup subdivided into the Bababudan Group and the Chitradurga Group), the two being separated by a gneiss forming event at 3 Ga. In the absence of unambiguous and precise primary chronologies of the high grade Sargur assemblages and the low grade basal sections of the Dharwar Supergroup relative to themselves and to the 3.0 Ga gneiss, the separation of the supracrustals into the Dharwar and Sargur cycles remains debatable. The demonstrable lithological similarities between the basal sections of the Dharwar supracrustals and the Sargur assemblages have been used to argue for contemporaneous deposition of the two.

Whereas the ages of the intrusive granites and volcanics of the Chitradurga Group at about 2.6 Ga indicate that the Dharwar supracrustals are older than this, the possibility that at least the basal formations of the Dharwar Supergroup may be older than 3.0 Ga and in fact coeval with the Sargur rocks has not yet been ruled out. The time span for the development of the entire Dharwar sequence needs to be precisely determined, as this sequence has signatures which are rather unusual for the Archaean, but normal to the Proterozoic, such as distinction of stable and mobile zones of sedimentation, stability during the initial stages of development of supracrustal sequence, deposition of uraniferous conglomerates, large scale development of limestones, banded manganese and iron formations and stromatolites.

The third major granite-gneiss forming event occurred 2.5 to 2.6 Ga ago marking the close of the Dharwar tectonic cycle and remobilising the preexisting gneisses accompanied by large scale potash metasomatism. The Peninsular Gneissic complex with three distinct age components (3.4, 3.0 and 2.6 Ga) resulted by the close of this episode. The earliest granulite grade metamorphism so far recognised seems to be synchronous with this event. Evidence for 3.0 Ga and 2.6 Ga events have been found also in the granulite terrane including the Eastern Ghat belt. The relicts, if any, of the earlier 3.4 Ga event have not yet been picked up from the granulite province.

Geochronologically least constrained are the khondalites which resemble the Sargur supracrustals and may be high grade derivatives of the Bababudan Group and the Vanivilas Formation of the Chitradurga Group. Khondalites are known to have been intruded by charnockites in the Eastern Ghats. But whether these charnockites are as old as 2.6 Ga charnockites in the southern granulite zone or even older (3.0 Ga) needs to be assessed. In this context, it is to be noted that charnockites retrograde to gneisses and vice versa in several places. Charnockites retrograding to gneisses, but unconfined to later shear zones where such retrogression is common, could in fact belong to the older 3.0 Ga event.

One prevelant view is that the formation of potash granites of the Closepet suite occurred during the 2.6 Ga event in the upper crust coinciding with the charnockitization in the lower crust. Yet there are Rb-Sr ages as young as 2.1 Ga for some Closepet granites. Was the charnockitization in the lower crust and potash granite formation in the upper crust a protracted event lasting for nearly 500 Ma?

In summary, urgent and systematic geochronological studies should address the following first order questions on the temporal evolution of the south Indian crust.

1. Do the Sargur supracrustals predate the 3.4 Ga old gneissic components of the Peninsular Gneissic complex?

2. If not, are they older or only coeval with the lower Dharwar supracrustals and khondalites?

3. What is the time span for the development of the entire Dharwar supracrustal sequence?

4. What is the time relation between the 3.0 Ga old gneisses and the lower Dharwar supracrustals in the Craton and the khondalites in the Eastern Ghats?

5. Are there more than one generation of early Precambrian charnockites, just as there are more than one generation of gneisses?

6. Are the metamorphosed mafic dike swarms directly linked to the episodes of volcanism and plutonism in the early Precambiran of south India?

HEAT FLOW, HEAT GENERATION AND CRUSTAL THERMAL STRUCTURE OF THE NORTHERN BLOCK OF THE SOUTH INDIAN CRATON

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Heat flow values (Gupta et al. 1982, 1986, 1987 plus some new data) and heat generation data calculated from the concentration of heat producing radioactive elements, U, Th and K in surface rocks (Atal et al.1978; Allen et al. 1985; Condie and Allen, 1984., Gupta et al. 1986., Janardhan et al. 1983., Narayana et al., 1983., Naqvi, 1981., Rao et al., 1976., Reddy et al. 1983. of the Northern block of the South Indian Craton (SIC) have been analysed. The SIC, according to Drury et al., (1984), can be divided into various blocks, separated by late Proterozoic shear belts. The northern block comprises Eastern and Western Dharwar Cratons of Rogers (1986), Naqvi and Rogers (1987) and a part of the South Indian granulite terrane up to a shear system occuping the Palghat - Cauvery low lands.

We obtain:

that the heat flow in granite-greenstone belts is low (mean heat flow Q=33 mWm^{-2}, number of determinations n=7), and is normal (Q=40 mWm^{-2}, n=6 - more or less equal to the mean heat flow for the Precambrian Shields) in the vast granitic-gneissic terrane.

that the heat flow data in Proterozoic Cuddapah Basin show a large variation - values from 27 mWm^{-2} to 75 mWm^{-2}. The low value is from an area near its south-western margin where the whole crust has become more or less basic due to intrusions and the high values (50 to 75 mWm^{-2}) are near its north-eastern margin close to an exposed large sized granitic dome.

that a wide scatter occurs in heat production in almost all near surface rocks (Table 1). However, the charnockites and the greenstone rocks are associated by low values of radio-active heat generation.

Reliable heat flow (Q) and heat generation (Ao) pairs for SIC yield values of reduced heat flow (Qr) and the thickness (D) of the top radioactive layer as 23 mWm^{-2} and 11.6 km respectively. However, keeping in mind the existence of great geological heterogenity both in lateral and vertical direction in SIC and similar such terranes, observation of a linear relationship between Q and Ao may be a mere coinsidence. Consequently its use in estimating lower crustal and mantle heat flow (Qr) and the lower crustal temperatures would result in wrong estimates. Alternate suitable method to overcome this difficulty will be presented along with crustal temperature profiles.

It has been generally recognised that the northern block of the SIC, in litho-logical terms, is similar to Archaean terranes in North America, Africa and Australia (Drury et al. 1984). A comparison of its geothermal parameters with those of the Western Australian Shield (WAS), (Sass et al. 1976) has been attempted.

We obtain:

that the heat flow in granite greenstone belt of WAS is also low (mean heat Q=35 mWm^{-2}, n=13), and is normal in its granite-gneiss terrane (Q=44 mWm^{-2}, n=3).

Further the radioactive heat production in near surface and crustal rocks of WASin no way appears to be lower than in the rocks of the northern block of the SIC (Table 1). In fact the data reveal that the heat generations in greenstones, granites and gneisses of the SIC and WAS from granite-greenstone terranes have more or less similar values. The same appears to be the case for granite-gneiss terranes. Other geophysical parameters support existence of more or less similar lower crustal conditions both under SIC and WAS.

The geothermal data clearly demonstrate that the present thermal characteristics of the above two Archaean terranes of the Indian and Australian Shields are quite similar. Their crustal thermal structures are likely to be similar also.

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TABLE 1: RADIOACTIVE HEAT GENERATION (Ao, μWm^{-3}) IN SURFACE ROCKS, NORTHERN BLOCK, SOUTH INDIAN CRATON AND WEST AUSTRALIAN SHIELD

Rock Type/Area	N	Ao μWm^{-3}	Rock Type/Area	N	Ao μWm^{-3}
GRANITE			GREENSTONE BELTS		
Hyderabad	29	5.57	Kolar belt		
Arsikere	9	3.08	a) Hornblende schist	15	0.26
Chikmagalur	6	1.28	b) Amphibolite	5	0.26
Closepet	5	1.81	c) Granites and		
Chamundi	2	3.40	gneisses	5	3.12
GRANITIC PEBBLES			JAVANHALLI BELT		
Kaldurga	9	1.06	a) Na-rich (gn)	-	2.17
Aimangala	7	1.51	b) K-rich (gn)	-	1.91
			c) Para-amphibolite	-	0.18
GNEISSES (gn)					
Champion (gn)			HOLENARASIPUR BELT		
around Kolar	29	1.51	a) Granite/gneisses	5	1.38
Grey (gn)	5	1.98	b) Anorthosite	1	0.10
Tonalite/trondh-			c) Amphibolite	6	0.23
jemite	2	0.53	d) Metapelite	6	1.08
Peninsular (gn)			e) Fuchsite quartzite	4	0.05
Bangalore Dist.	9	1.80			
CHARNOCKITES			CHITRADURGA BELT		
a) low grade	5	0.37	a) Metavolcanic	3	0.15
b) medium grade	4	0.32	b) Graywacke	2	0.62
c) high grade	9	0.23	c) Phyllite	1	0.92
			d) Pebbles (granitic)	7	1.51
GNEISS-CHARNOCKITE			e) Pebbles (diorite)	-	0.15
PAIRS: (PROGRADE)					
Gn	2	2.38			
Ch	2	1.68			
		WEST AUSTRALIAN SHIELD			
GRANITE			GRANODIORITE		
Mount Magnet	7	6.80	Yakab-mount Goode	6	1.88
Kambalda	13	1.29	Gneissic granite	5	1.17
Widd-Wanaway	4	1.15	PYROXENE GRANULITE		
Woolgangie	54	3.18	Kalgoorlie	60	0.54
GRANITIC GNEISS			GREENSTONE BELT	57	0.29
Doodlakine	36	8.90	West Australian	large	2.42
Northam	84	2.13	Shield		

PETROCHEMICAL AND PETROPHYSICAL CHARACTERIZATION OF THE LOWER CRUST AND THE MOHO BENEATH THE WEST AFRICAN CRATON, BASED ON XENOLITHS FROM KIMBERLITES

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Notwithstanding the attention given over the past several decades to the genesis of the crust, interpretations of the nature of the continental lower crust remain diverse and opinions differ widely as to whether the lower crust is hydrated or anhydrous, and mafic or felsic. The present study attempts to constrain models of the lower crust and upper mantle through integration of petrochemical and petrophysical properties of a suite of granulites (garnet anorthosites to garnet pyroxenites) and eclogites from the Man Shield of the West African Craton. Age provinces in the shield are Leonean (~3.0 Ga), Liberian (~2.7 Ga), and Eburnean (~2.0 Ga), and these are fault bounded by the ~550 Ma Pan African age province. Crustal granulites and upper mantle eclogites were sampled as xenoliths from diamondiferous kimberlites of Cretaceous age (90-120 Ma) which were intruded into Liberian age province granitic gneisses in Liberia and Sierra Leone.

Most of the granulites are typical of those from elsewhere in Africa (1) and other world-wide locations (2), but some apparently differ in three significant respects: firstly in the presence of iron metal (3), secondly in the effects of metasomatism (4), and thirdly in aspects of partial melting. Native iron of low Ni and Co content, in association with scapolite and/or a highly aluminous (18-21 wt% Al_2O_3) tschermakitic amphibole, was formed by decomposition of almandine-rich ($Alm_{51-56}Pyr_{27-32}Gross_{14-17}$) garnet. Iron metal also resulted from ilmenite decomposition in which iron, ulvöspinel, troilite, and FeTiS were formed. Temperature estimates are 830-1000°C at fO_2's at or below iron-wüstite (IW). Metasomatism is manifest in the formation of scapolite (60-75 % Me), and also in rims of ferro-freudenbergite ($Na_2FeTi_7O_{16}$) around nucleii of rutile, a reaction in which ilmenite, perovskite, and sphene were also formed (4). Metasomatic fluids or partial melts were enriched in Na, Fe, Ca, and Si in contrast to those typical of upper mantle metasomatism in which metasomatic enrichment is characterized by K, Ba, Sr, Ti, LREE, Nb, and Zr (5). Partial melting of the granulites, specifically of garnet and plagioclase, yielded clinopyroxene + kyanite + scapolite. A characteristic feature of these classes of granulites is the presence of graphite.

Major element XRF analyses, petrographic and electron microbeam mineral chemistries, densities, magnetic properties, and calculated P-T and seismic P-wave velocities (V_p) have been determined for most of the larger specimens of granulite, and for selected eclogites and anorthosites. A chemical continuum between these lithologies has been established (Fig. 1). High Mg eclogites, approaching komatiitic basalts in composition, grade progressively into low Mg eclogites (of alkali hawaiite affinity), granulites (of high alumina alkali basalt composition), and garnet anorthosites. For these xenoliths, specific gravity (SG) is directly proportional to FeO + MgO and inversely proportional to alkalies and to SiO_2. Seismic P-wave velocities for the low Mg eclogites and the granulites, estimated from SG (6), show a range from 6.6 to 8.7 km/sec with a transitional group between typical crustal and mantle values which is comprised of both lithologies (Fig. 2). Magnetic susceptibilities and NRM values of the granulites are shown as functions of SG, wt% FeO, and wt% SiO_2 in Fig. 3; assuming that V_p, SG, and FeO increase and SiO2 decreases with depth then the induced and remanent magnetizations increase in intensity within the lower crust (7). Ferromagnetism may persist within the upper mantle to 90 km depth (3), or to shallower depths (~70 km) if upper mantle metasomatism induces relatively oxidized horizons (8). P-T estimates and a geothermal gradient derived for the eclogites and granulites (9) lie between the gradients commonly assumed for cratonic surface heat flows (~40 mW/m^2) and typical rift environments (~90 mW/m^2).

Granulites, eclogites, and garnet anorthosite xenoliths from the West African Craton appear to be petrologically, geochemically, and geophysically related, although some show evidence of subsolidus reduction and decomposition, metasomatism, and partial melting. The continuum in bulk chemistry and P-wave velocity strongly implies that the lower crust - upper mantle boundary between 40 and 70 km (Fig. 2) is not a simple petrological discontinuity but is instead at least in part an intercalated granulite-eclogite transition zone that may have resulted from igneous fractionation, metamorphism, and partial melt underplating in a developing continental lithosphere. From diamond inclusion evidence, the subcratonic lithosphere is dominantly ultramafic and is inferred to be at least 200 km thick and Archean in age, an age in accord with the oldest surface rocks of the West African Craton. Felsic rocks form a minor component of the lower crust of this craton, and hydrated mineralogies are clearly superimposed or are the by-product of re-equilibration. Hence the continental lower crust of the Man Shield is dominantly anhydrous, mafic, and reduced in redox state.

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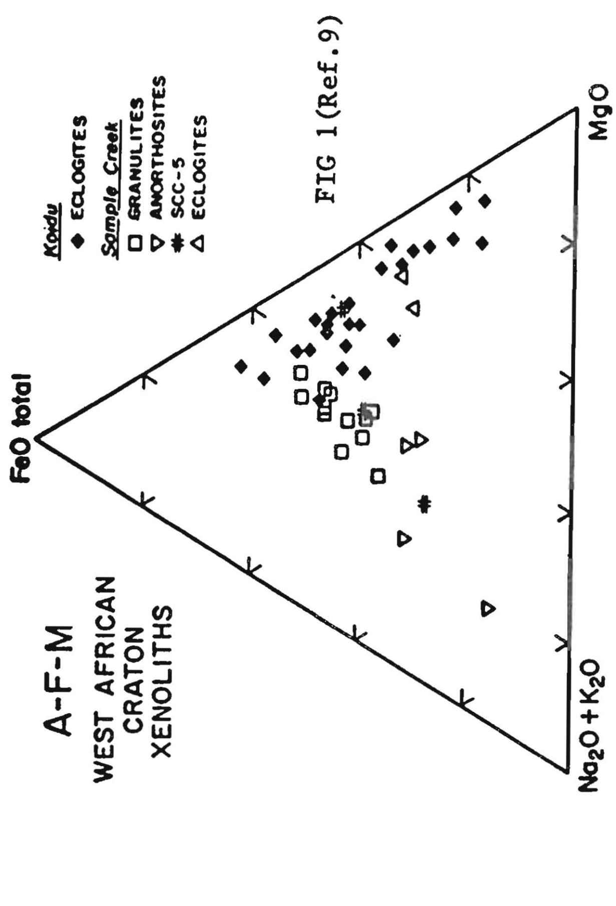

FIG 1 (Ref.9)

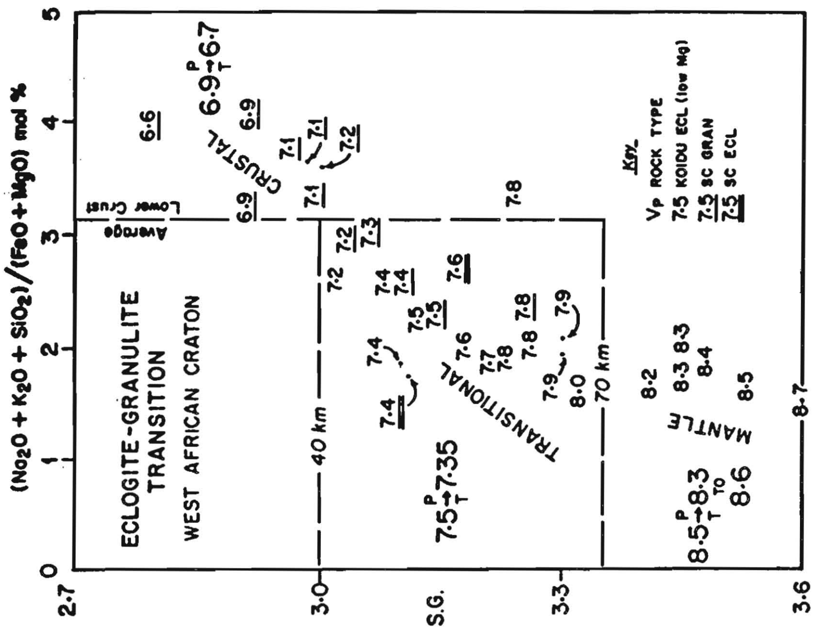

FIG 2 (Ref.9)

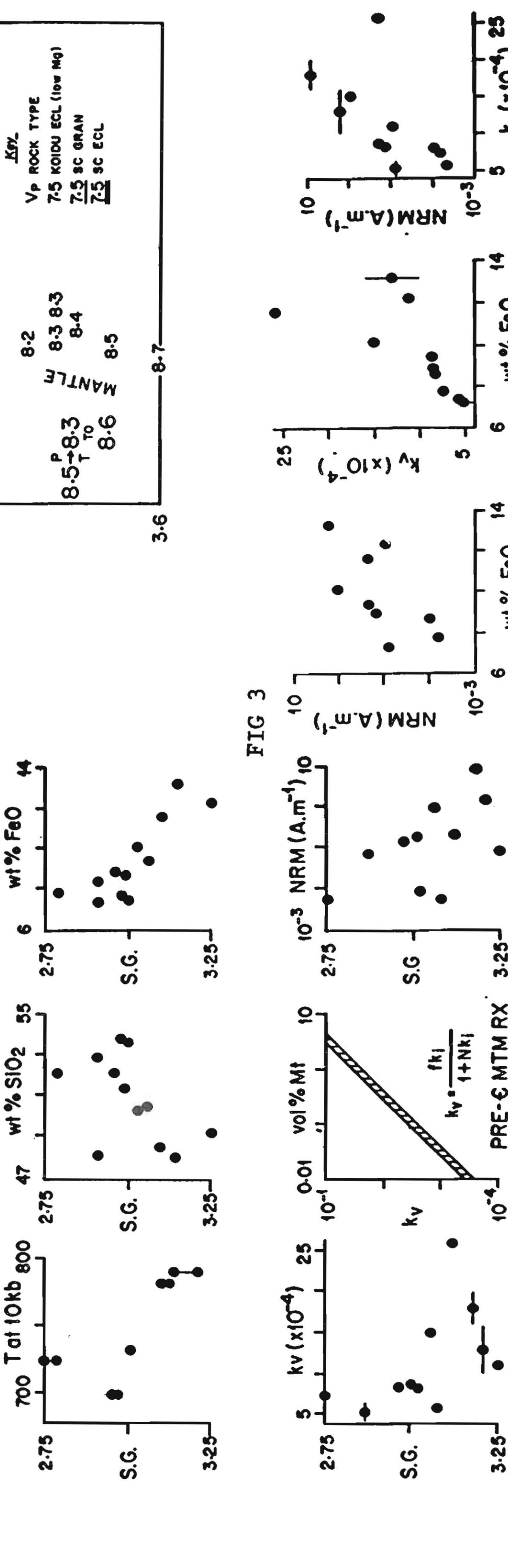

FIG 3

Evidence for CO2-rich fluids in rocks from the "type" charnockite area near Pallavaram, Tamil Nadu

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Charnockitic rocks were first described by Sir Thomas Holland (1900) from the hills around the village of Pallavaram south of Madras. In this area a series of acid to intermediate magmas intruded an interbedded sequence of predominatly pelitic and mafic rocks which were latter metamorphosed to high grade (Subramaniam, 1959). According to Weaver (1980) chemical trends in the charnockites indicate a period of metasomatism and partial melting immediately preceeding the granulite-facies metamorphism which he suggests was due to an influx of CO2-rich fluids. On the other hand, Bhattacharya and Sen (1986) concluded that no pervasive fluid was present during the high-grade metamorphism which involved internal buffering of fluids and dehydration melting. They based their conclusions largely on calculations of metamorphic water activities which are different for different rock types and show systematic variations with mineral chemistry. We have examined rocks from a quarry southeast of Pallavaram for evidence indicating the concentration of carbon-dioxide in the metamorphic-fluid phase.

Charnockitic rocks are the major rock type exposed in the quarry. These rocks are cut by coarse-grained dykes and veins also made up of dark charnockite. Mafic granulites occur as enclaves. One especially large mafic enclave contains light colored veins made up of calcite and scapolite with smaller amounts of diopside and quartz. Garnets are concentrated at the margins of these veins. The dark host rock has a granulitic texture and is made up of hornblende, diopside, plagioclase and quartz with sporadic garnet.

Results of EDS electron-microprobe analyses on minerals from the mafic host and calcite-bearing veins are given in Table 1. W.D.S. analyses of the scapolite indicate only small amounts (less than 0.1 wt%) of sulfur or chlorine. The mineral assemblage at the edges of the vein allow us to estimate the CO2 concentration in the metamorphic fluid using the reaction:

meionite + 5 calcite+ 3 quartz = 3 grossular + CO2.

Calculations using the thermodynamic data of Holland and Powell (1985) indicate a nearly pure CO2 fluid under the metamorphic temperatures (750-800^{o}C) and pressures (6.5 - 7.5 kbars) obtained for the area by Bhattacharya and Sen (1986).

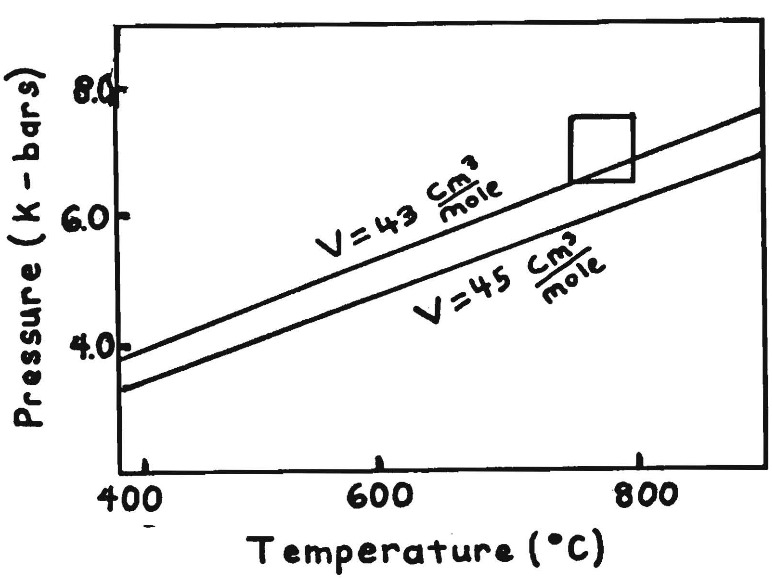
Carbonic fluid inclusions are abundant in a sample of one of the coarse-grained charnockitic veins collected near the mafic enclave. The vein is roughly granitic in composition containing the assemblage alkali-feldspar, plagioclase, quartz, orthopyroxene and opaques. The fluid inclusions occur in planar arrays and are hence secondary or pseudosecondary. Melting temperatures obtained on these inclusions are all within 1^{o}C of the melting temperatures of a pure CO2 standard. Thus the fluid is nearly pure CO2 although small (up to about 20%) amounts of water may be present

Table 1 - Mineral Compositions

	Garnet Host Rock	Garnet Vein	Diopside Host Rock	Diopside Vein	Scapolite Vein	Plag Host Rock
SiO_2	37.6	37.7	50.5	48.3	42.9	49.7
Al_2O_3	21.5	21.0	2.3	2.5	30.2	33.1
FeO	27.4	25.9	16.8	24.1		
MnO	1.3	0.8				
MgO	2.3	1.5	8.9	4.5		
CaO	10.8	13.3	21.9	21.7	20.4	15.1
Na_2O					1.6	2.1
Total	100.9	100.2	100.4	101.1	95.1	100.0
Si	2.94	2.99	1.94	1.92	6.59	2.26
Al	1.99	1.96	0.10	0.12	5.47	1.77
Fe	1.79	1.72	0.54	0.80		
Mn	0.09	0.06				
Mg	0.26	0.18	0.52	0.27		
Ca	0.91	1.13	0.90	0.93	3.37	0.74
Na					0.47	0.19

as a thin, undetected, immiscible layer against the walls of the inclusions. Homogenization temperatures cluster between $-9^{\circ}C$ and $-18^{\circ}C$ and hence have specific volume between 43 and 45 cm^3/mole. Isochores for those two volumes, calculated with the equations of Touret and Bottinga (1979) are given in Figure 1. The box in the figure outlines the metamorphic conditions for the area deduced by Bhattacharya and Sen (1986). Isochores for the denser fluid inclusions pass through this box. If small amounts of water are present as an immiscible fluid, then the isochores in Figure 1 should be moved to slightly higher pressures and this would increase the overlap with the metamorphic conditions.

Figure 1



The fluid inclusions indicate that a dense CO_2-rich fluid was present at some point in the history of the charnockite. It is difficult to see how the mineral assemblages in the charnockite or its igneous precursor could have generated CO_2, hence it probably flowed in from the outside. The densities of these fluids are approximately consistent with entrapment at peak metamorphic conditions as would be predicted by the CO_2-influx model of Weaver (1980). However, high densities are no guarantee that the fluid actually represents the peak metamorphic fluid nor is the presence of CO_2-rich fluids necessarily incompatible with other models of granulite-facies metamorphism (Crawford and Hollister, 1986).

An influx of CO_2 should lead to "carbonated" mineral assemblages in rocks of the appropriate bulk compositions. This may be the case with the carbonate-bearing veins in the mafic enclave, although it is by no means certain that the veins are metasomatic. The sporadic occurrence of garnet in the host rock without scapolite or calcite suggests lower CO_2 fugacities than in the veins and hence indicates some heterogenity in the metamorphic fluid phase. According to Subramaniam (personal communication, 1983) wollastonite-bearing veins had also been found in the mafic enclaves in this quarry. Wollastonite is not stable in the presence of a CO_2-rich fluid during granulite facies conditions (Valley, 1985) and hence its presence may indicate large heterogenites in the metamorphic fluid. Unfortunately, we were unable to locate any of the wollastonite-bearing veins and have little indication of how they fit into the metamorphic history of the area.

We have evidence that a dense CO_2-rich fluid was once present in the rocks exposed in the type charnockite area around Pallavaram. This gives some support to the idea proposed by Weaver (1980) that the granulite-facies metamorphism in this area was due to the influx of a CO_2-rich fluid. However, important questions still remain about the timing of CO_2 influx, the pervasiveness of the CO_2-rich fluid, and its source. Thus, for example, our results are also consistent with a model in which the bulk of the granulite-facies metamorphism occurred through dehydration melting accompanied or followed by some localized migration of CO_2-rich fluids. This is a model very similar to the one proposed by Bhattacharya and Sen (1986). More information will be needed, especially about the thermal history of the area and stable isotope compositions, before the role of the CO_2-rich fluid can be resolved.

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TECTONIC SETTING OF THE KOLAR SCHIST BELT, KARNATAKA, INDIA;

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The Archean Kolar Schist Belt has the key features of a suture zone, i.e. the juxtaposition of terranes of distinctly different gological histories. Based on geology, trace element geochemistry, initial, radiogenic-isotope ratios and geochronology, we recognize at least four different terranes consisting dominantly of: 1) felsic gneisses to the east of the belt, 2) felsic gneisses to the west of the belt, 3) amphibolites in the west central part of the belt, and 4) amphibolites in the eastern part of the belt (Fig. 1).

West of the belt, granodioritic gneisses were emplaced at 2632±8 Ma, 2613±10 and 2553±3 Ma and metamorphosed at 2553±2 Ma. These gneisses have inherited zircons from an older basement at least 3200 Ma old. The Pb, Sr, and Nd isotopes have a continental signature also suggest that a ca. 3200 Ma, or older, basement contaminated the magmas parental to the western gneisses (1).

East of the belt, the gneisses were emplaced at 2532±3 Ma and cooled or were metamorphosed at 2521±2 Ma. The Pb, Sr and Nd isotope data for these gneisses have a mantle signature. These isotopic and age differences suggest that the two gneiss terranes had separate histories until some time after 2521 Ma (1).

Within the schist belt the komatiitic amphibolites to the east are dominantly light REE enriched and those in the west-central part are dominantly light REE depleted and each has a distinctly different Pb isotope character (2,3). The west-central, komatiitic amphibolites give a Sm-Nd age of 2690±140 Ma and the west-central tholeiitic amphibolites give a Pb-Pb isochron age of 2733±155 Ma(2), suggesting that some of the amphibolites may be older than the 2530 to 2630 Ma gneisses to the east or west of the belt.

Surprisingly, the Pb isotope ratios for the tholeiitic amphibolites from the west-central part of the belt are significantly different from the Pb isotope ratios for interlayered komatiitic amphibolites, suggesting that the parental magmas of the tholeiitic amphibolites are derived from sources with a quite different U-Pb history than the parental magmas of the komatiitic amphibolites (2). Rajamani et al.(3,4) suggest that while the west central komatiites are derived by melting at pressures of about 50 Kb from a mantle source with an Fe/Mg ratio somewhat greater than that for pyrolite, the tholeiites are derived by melting at pressures less than 25 Kb from a source with a much higher Fe/Mg ratio than that for the komatiites.

The long-lived depleted light REE depleted character of the west-central komatiitic amphibolites (2) suggests that if there were an Archean MORB source, these komatiitic amphibolites are candidates for derivation from such a source. The tholeiitic and komatiitic amphibolites may be tectonically interlayered. Or, the tholeiites may have been intrusions. If, however, they were developed at the same time and place, we would suggest an asthenospheric source for the komatiitic amphibolites and a subcontinental lithospheric source for the tholeiites.

The eastern amphibolites have not been dated, but their Nd and Pb isotope character suggests an age of ca. 2700 Ma(2). The light REE enrichment and distinctly different Pb isotope character of the eastern amphibolites, suggest that they were derived from a mantle source with a REE and U-Pb history quite different from that of the west-central amphibolites. This would also suggest that they formed in different settings on the surface of the earth.

Fig. 2 shows in block diagrams the timing and development of the Kolar Schist Belt. At about 2700 Ma, the parental rocks of the eastern and west-central parts of the schist belt developed in potentially widely separated environments. The western terrane consisted only of the 3200 Ma or older basement. The eastern terrane did not exist. By 2530 each of the terranes had developed their major lithologic character, but were probably not yet juxtaposed. By 2420 Ma, a time of major shearing and metamorphism (1), the different terranes were juxtaposed.

A plate tectonic and uniformitarian model could explain many of the features of the Kolar Schist Belt and surrounding gneisses. The parents for the west-central komatiitic amphibolites may have been the Archean equivalent of modern mid-ocean ridge or back-arc-basin basalts derived from a long-lived, incompatible-element-depleted mantle source. Ocean ridge melts may have been komatiites due to the higher heat budget during the Archean. If the parents of the west-central, tholeiitic amphibolites formed at the same time and place as the parents of the komatiitic amphibolites, a setting more like that of a back-arc basin would be required in which a long-lived, perhaps subcontinental lithosphere could be the source for the parents of the tholeiitic amphibolites and the underlying aesthenosphere could be the source for the parents of the komatiites. If the komatiites and tholeiites were interlayered tectonically or either are intruding the other, then the tholeiitic and komatiitic parents could have formed in different locations and at different times. The parents for the eastern komatiitic amphibolites could have been the Archean equivalent of modern ocean island or island arc basalts.

The character of the plutonic rocks of the western gneisses and their setting upon an older basement, is compatible with the development of a magmatic arc on the edge of a continent. We do not have an explanation for the tectonic setting for the eastern gneisses, which are typical of many Archean granitoid rocks in that they have mantle isotope signatures, but are geochemically quite evolved.

We would suggest that: 1) the multiple phases of folding, resulting in refolded isoclinal folds in the iron-formation due principally to E-W subhorizontal shearing followed by longitudinal shortening (5), 2) the late N-S left lateral shearing found in all rocks, and 3) the disparate geologic terranes are features very similar to those geologic features found in the accretionary terranes of western North America (6).

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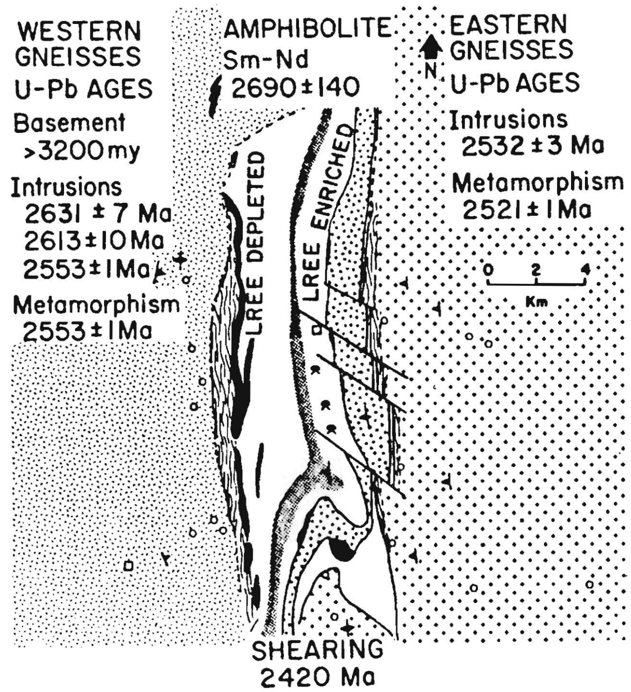
Fig. 1. Geological sketch map of the central part of the Kolar Schist Belt. The basement age for the western gneisses is based on Pb/Pb ages for the cores of zircons from and Pb and Nd isotope data for the ca. 2600 Ma western gneisses. Intrusive and metamorphic ages for the gneisses are the U-Pb ages for zircon and sphene respectively. The age of shearing is based on an Ar/Ar plateau age for muscovite developed in the shear zone. The Sm/Nd isochron age is for the western komatiitic amphibolites.



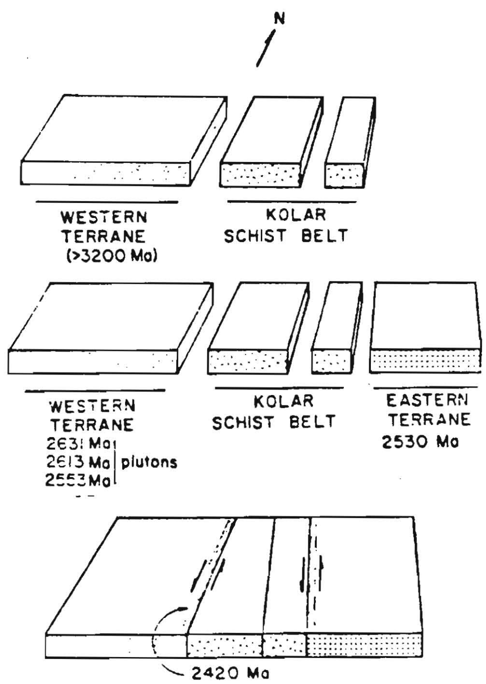


Fig. 2. Block diagram showing the crustal evolution in the Kolar area.

CL-RICH MINERALS IN ARCHEAN GRANULITE FACIES IRONSTONES FROM THE BEARTOOTH MOUNTAINS, MONTANA, USA: IMPLICATIONS FOR FLUIDS INVOLVED IN GRANULITE METAMORPHISM.

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INTRODUCTION. Although Cl-rich minerals have been recognized to develop in a number of petrologic environments ranging from submarine hydrothermal vents [1] to late mafic pegmatitic dikes and Pt-rich horizons in layered magmatic intrusives [2,3], they are most commonly found in granulite facies rocks. It is probably the earlier work on the high grade terrains of South India that most clearly demonstrated this [e.g. 4,5,6,7,8]. Nonetheless, most of the investigations on Cl-rich minerals from granulites dealt primarily with their chemical characterization but have not considered their petrologic implications. Clearly, before fully understanding granulite facies metamorphism the role of Cl in granulites must be explored.

There are three factors that influence the incorporation of Cl into hydrous silicates and phosphates: fluid composition, temperature and crystallochemical constraints. It has been experimentally confirmed that as chlorinity and acidity in an aqueous fluid increase and/or as temperature increases, the Cl concentrations in the coexisting micas also increase [9,10]. Experimental studies have also established that the compositional parameters (especially increasing ferrous Fe contents) that enable the hydroxyl site to approach ideal hexagonal symmetry in hydrous silicates strongly favor Cl incorporation [11].

With these factors in mind, the hydrous minerals of the granulite facies ironstones from the Beartooth Mountains, Montana are considered in this investigation.

BACKGROUND. The eastern portion of the Beartooth Mountains, composed predominantly of 2800 Ma granitic to tonalitic granitoids, gneisses and migmatites, contain enclaves of various supracrustal lithologies that range in size from a few cm to a few km [12]. The supracrustal lithologies, including pelitic schists, felsic gneisses, amphibolites, mafic gneisses, quartzites and ironstones, typically display mineral assemblages that are indicative of granulite facies metamorphism [13]. Application of a series of geothermobarometers indicate that the peak metamorphism took place at pressures of 5-6 kbar and temperatures of 750-800 C. Some of the lithologies are partially-to-completely reset by a subsequent amphibolite facies metamorphism that is attributed to the major magmatic event at 2800 Ma. The Rb-Sr isotopic systematics on the supracrustal lithologies produce a poorly constrained isochron of approximately 3400 Ma that has been interpreted as the time of the granulite facies metamorphism [12].

MINERALOGY AND PETROLOGY OF THE IRONSTONES. The iron-rich metasedimentary rock of the eastern Beartooth Mountains is a typical quartz-magnetite banded iron formation with bulk compositions ranging from 47 to 61 weight % SiO_2, 30 to 40 % FeO and 1 to 3 % Al_2O_3. The bulk compositions and REE abundances indicate an origin of the ferruginous sediment on a continental shelf rather than a eugeoclinal depositional environment [12].

The mineral assemblages of the ironstones are, in general, similar to other granulite facies ironstones [14] with the most common assemblage being quartz + magnetite + ferrohypersthene + almandine + clinopyroxene. In addition, there are trace or minor amounts of a blue-green amphibole and dark brown biotite that are found as both inclusions and matrix phases. As such, they are interpreted as having been involved in the prograde metamorphism of the ironstones. Very minor amounts of cummingtonite after ferrohypersthene and actinolite after clinopyroxene localized along later fractures indicate the subsequent amphibolite facies metamorphism did not significantly affect the ironstones.

Based on calculations of coexisting mineral compositions it is estimated that the fluid phase has an $X(H_2O)<0.3$ and is relatively oxidizing (near the NNO buffer). "Primary" fluid inclusions are apparently CO_2-rich suggesting CO_2 is the dominant component in the fluid phase.

Both the biotites and amphiboles found in these ironstones have some of the highest Cl levels that have been documented to date (with the biotites and amphiboles in the matrix containing more Cl than the biotite and amphibole inclusions in garnet and ferrohypersthene). The biotites not only contain up to 2.9 wt % Cl (22 % of the OH site), but also have substantial amounts of Ba (up to 10.5 wt%) and Ti (up to 6.9 wt %) (see Table 1). The amphiboles contain up to 2.8 wt % Cl (40 % of the total OH site) and range in composition from a ferroan pargasite to a Cl-rich potassium hastingsite (see Table 1). In these minerals there is a general positive correlation among Cl levels and Fe, Ba and K (in amphiboles). These trends are in accordance with the expected crytallochemical controls of Cl incorporation.

Not all of the Cl variations, however, are purely controlled by the crystallochemical constraints. Based on the Cl contents of the biotites, the relative $f(H_2O)/f(HCl)$ ratios [10] range from 0.02 to 1 suggesting that some of the biotite variability must result from changes in the local fluid compositions. These calculations indicate the that the amount of HCl in the fluid must be substantial and are probably only attained in an aqueous fluid. Furthermore, the increasing Cl-enrichment of the matrix biotite and amphibole relative to the included biotite and amphibole suggest an increasing chlorinity with grade. Nonetheless, based on fluid calculations and fluid inclusion work it is known that the dominant fluid is a CO_2-rich fluid. Such a fluid will not support the high levels of Cl necessary to produce the elevated Cl contents in the silicates [cf. 15]. Consequently, we must entertain the possibilty of an immiscible highly saline and acidic aqueous fluid coexisting with the dominant CO_2 fluid typically found in granulites.

IMPLICATIONS. Evidence for CO_2-brine immiscibility have been found in some medium grade metamorphic rocks [e.g. 15,16]. However, this current study indicates that this immiscible behavior of fluids may extend into granulite facies conditions.

The presence of such a high grade immiscible fluid may have significant affects on the behavior of granulite fluids. The aqueous brines may be preferentially absorbed on the surfaces of minerals relative to the nonpolar CO_2 fluid phase resulting in differential movement of the unmixed brine and CO_2 fluids [17]. Due to its capacity to form complexes, Cl-rich aqueous brines have been implicated in the movement of elements such as Pt group elements, Pb and rare earth elements [2,18].

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TABLE 1. Representative Cl-rich biotite and amphibole analyses

Sample name	QC82-45	QC82-45	QC81-113	QC82-45	QC82-45	QC-IS
Analysis pt	BIOTITE 1	BIOTITE 2	BIOTITE 3	AMPHIB 1	AMPHIB 2	AMPHIB 3
Remark	MATRIX	OPX INCL	OPX INCL	MATRIX	GAR INCL	MATRIX
SiO2	28.79	30.58	33.28	37.11	37.97	39.70
Al2O3	14.12	13.88	15.05	11.38	10.86	11.78
TiO2	6.29	5.84	1.02	1.40	1.84	0.12
Cr2O3	0.00	0.00	0.02	0.04	0.04	0.01
FeO	29.08	29.37	27.14	27.28	25.75	24.96
MnO	0.11	0.10	0.13	0.17	0.17	0.26
MgO	2.29	3.96	6.66	3.83	4.96	5.70
CaO	0.02	0.01	0.03	11.50	11.62	11.52
Na2O	0.00	0.05	0.08	0.65	1.06	0.61
K2O	5.47	6.93	8.18	3.20	2.39	2.97
BaO	9.65	7.25	2.90	0.55	0.53	0.19
Cl	2.74	2.26	2.41	2.61	1.82	1.34
F	0.10	0.07	0.07	0.08	0.25	0.21
SO3	0.00	0.17	0.00	0.03	0.04	0.00
	------	------	------	------	------	------
Total	98.66	100.47	96.97	99.81	99.30	99.37
O=F,Cl	0.66	0.54	0.57	0.62	0.52	0.39
	------	------	------	------	------	------
TOTAL	98.00	99.93	96.40	99.19	98.79	98.98

CO_2-RICH FLUID INCLUSIONS IN GREENSCHISTS, MIGMATITES, GRANULITES, AND HYDRATED GRANULITES; L.S. Hollister, Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ 08544

The discovery of pure CO_2 fluid inclusions in granulite facies rocks stimulated models (1,2) attributing a causative role of CO_2 fluids to the formation of granulite facies rocks. The studies of Janardhan et al. (3) and Hansen et al. (4) make a strong case that charnockites in south India were formed by CO_2 infiltration into gneiss; the argument is primarily supported by the occurrence in the charnockites of abundant, "pure" CO_2 fluid inclusions. Hansen et al. (4) and Newton (5) show that a fluid in equilibrium with the mineral assemblages at the calculated metamorphic conditions would be CO_2-rich, and that the fluid inclusions not only are CO_2-rich but also have densities appropriate for the metamorphic conditions. Even though the inclusions appear to be pure CO_2, as much as 30 mole percent H_2O may be present as an optically unresolvable film on the walls of the inclusions (4,6). This allows some reconciliation of the results of the microthermometric data with those of mineral equilibria calculations.

Reports of CO_2-rich fluid inclusions from parageneses for which H_2O-rich fluids have been predicted, however, raise the possibility that the agreement between prediction and observation for the granulite facies terranes may be coincidental. There may be a common process which leads to formation of CO_2-rich secondary inclusions in metamorphic rocks. This possibility needs be tested by well constrained studies of fluid inclusions at all grades of metamorphism and for metamorphic rocks of known tectonic setting.

Examples of discordance of composition of fluid inclusions with predicted composition include the greenschist to amphibolite facies terrane of south-central Maine for which an H_2O-rich synmetamorphic fluid has been predicted (7), leucosomes of migmatites for which X_{H2O} of the fluid phase had to be greater than 0.7 in order to have melt present at the reported P-T conditions (8), and graphite-bearing granulites for which calculations show that CO_2-rich compositions are not in equilibrium with the metamorphic assemblages (9,10). For the first two examples, CO_2-rich inclusions with densities appropriate for the metamorphic conditions have been reported (11,12,13). In the third case, the CO_2-rich inclusions have lower densities than the fluids would have had at peak metamorphic conditions (9,10). The occurrence and densities of the CO_2-rich inclusions from the greenschist facies rocks of southern Maine (11,12) are remarkably similar to those reported for southern Karnataka, India (4).

In a study of fluid inclusions (14) across the retrograde orthoamphibole isograd in the southern marginal zone of the Archean Limpopo belt of South Africa (15), patterns of composition and density of inclusions were also found to be similar to those reported from other granulite facies terranes, most notably Kerala, India (16): a few apparently pure CO_2 inclusions with densities appropriate for the P-T conditions, many CO_2 inclusions with lower densities, and aqueous inclusions of variable salinity and containing no detectable CO_2. The retrograde orthoamphibole isograd was apparently established by hydration of hot granulite facies rocks that had been thrust over a low grade granite-greenstone terrane (17). During or shortly after thrusting, volatiles generated by post thrusting heating of the footwall greenstones are hypothesized to have entered the granulite facies rocks of the hanging wall, leading to the hydration of the immediately overlying granulites and establishment of the retrograde orthopyroxene isograd. Metamorphic conditions at the isograd require that the equilibrium fluid had there an X_{CO2} of about 0.8. Our results suggest that the hydrating fluid may be represented by secondary CO_2-rich fluid inclusions, which may contain up to 30 mole percent H_2O.

The similarities of fluid inclusion populations are more striking than their differences for the above metamorphic terranes which have markedly different thermal histories. It appears, therefore, that we have some way to go before we can confidently relate, in all cases, entrapment of fluid inclusions to peak metamorphic conditions. This is not to say that fluid inclusion research in metamorphic rocks should not be pursued vigorously. Crawford and Hollister (18) review cases where fluid inclusions have been shown to be related to peak metamorphic conditions. Recently, Olsen (19) related fluid inclusions to conditions during anatexis. And a very productive use of studies of fluid inclusions in metamorphic rocks has been in constraining the post metamorphic exhumation histories of metamorphic terranes (16,20,21,22).

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Stable Isotope Studies on Granulites from the high grade terrain of Southern India

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Carbon dioxide-rich fluid inclusions from the high grade terrane of South India have been cited as evidence for granulite metamorphism resulting from pervasive carbon dioxide flushing, possibly from a deep seated source. This study tests the model of external CO_2-buffering and investigates the source of the carbon dioxide.

The terrain is thought to be of Archean age, and is segmented by Proterozoic shear zones. Samples of massive charnockites, precursor amphibolite gneisses and gneiss-incipient charnockite pairs from eight quarries throughout the high grade region have been analysed and representative results are shown in Table 1. Gas was extracted from fluid inclusions within quartz grains by a stepped heating technique[1].

All samples measured show similar and simple release patterns. A maximum carbon dioxide release is found between 600°C and 800°C, which is characterised by the isotopically heaviest carbon, ranging between -12‰ and -7‰. Optical fluid inclusion studies (M. Santosh) show that the majority of fluid inclusions in these samples rupture between 500°C and 800°C confirming them as the source for the analysed carbon dioxide.

The data when plotted on figure 1 illustrate that no systematic isotopic variation can be seen between gneiss and incipient charnockite as found in Kabbaldurga and Ponmudi. Furthermore massive charnockite which is exposed on a regional scale as in Madras or the Nilgiris has similar isotopic characteristics to incipient charnockite.

However the data clearly show that in all gneiss-incipient charnockite pairs quartz from the charnockite contains about three times more carbon dioxide than quartz from the gneiss. In the case of charnockites from South Kerala it is possible that some CO_2 results from oxidation of the graphite, which is present in significant amounts. However in Kabbaldurga and Koddakad where no graphite or other source of carbon is present fluid influx from an external source is the probable mechanism.

The uniformity of the $\delta^{13}C$ values of both gneisses and charnockites (averaging $-10 \pm 2‰$) from a wide area of South India indicates either that externally buffered CO_2 equilibrated with the gneiss or that the CO_2 now in the incipient charnockites represents a redistribution of the CO_2 in the precursor gneiss during charnockite formation. However we suggest that the greater abundance of CO_2 in incipient charnockites is compliant with an externally buffered CO_2 source rather than a closed system process. It seems unlikely that the source of the CO_2 can be wholly derived from crustal carbon (i.e. carbonates 0‰ and organic derived carbon -20 to -30‰) because of the apparent isotopic uniformity of the fluid. The range of $\delta^{13}C$ values for South Indian gneisses and charnockites are comparable to the composition of similar high pressure fluid inclusions preserved in upper mantle xenoliths (-8 to -14‰)[2] suggesting that such fluids may contain a significant mantle component. Many of the problems identified by this study may be resolved by ongoing analyses which will determine the carbon isotope characteristics of gneisses not associated with charnockites, and also the carbon isotope characteristics from fluid inclusions within charnockite phases critical to granulite formation such as biotiite and pyroxene.

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AREA	LOCALITY	ROCK TYPE	PEAK YIELD (ppm)	d13C
NILGIRIS	WELLINGTON (OOTY)	MASSIVE CHARNOCKITE	61	-8.9
MADRAS	PALLAVARUM	MASSIVE CHARNOCKITE	54	-9.6
BANGALORE	KABBALDURGA	GNEISS	10	-8.7
		INCIPIENT CHARNOCKITE	22	-9.5
PALGHAT GAP	KODDAKAD	GNEISS	17	-8.1
		INCIPIENT CHARNOCKITE	48	-7.9
SOUTH KERELA	PONMUDI	GNEISS	22	-10.1
		INCIPIENT CHARNOCKITE	76	-10.4
	KOTTAVATUM	GNEISS	11	-8.9
		INCIPIENT CHARNOCKITE	34	-9.2
	MANALI	GNEISS	42	-11.7
		INCIPIENT CHARNOCKITE	150	-7.6
		BASIC GRANULITE	48	-12.4

TABLE 1

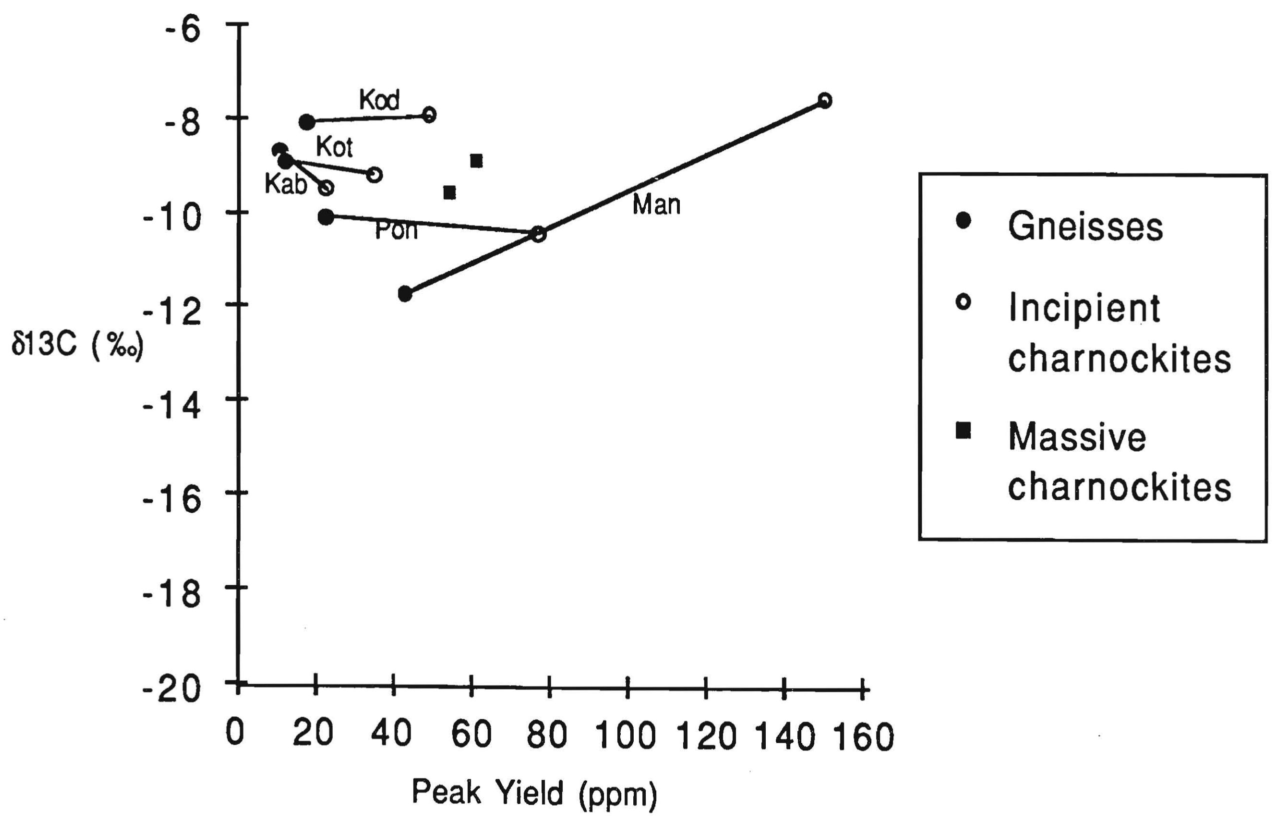

Figure 1

CHEMISTRY OF THE OLDER SUPRACRUSTALS OF ARCHAEAN AGE AROUND SARGUR

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In the Archaeans of the Karnataka craton two stratigraphically distinct volcano-sedimentary sequences occur, namely the older supracrustals of the Sargur type and the younger Dharwar greenstones. The dividing line between these is the 3 by old component of the Peninsular gneiss.

The Sargur supracrustal rocks are seen as tight to isoclinally folded remnants of quartzite-k-pelite-carbonate-BIF association in the Archaean tonalitic to trondhjemitic gneisses. These gneisses around Gundlupet give an age of 2850 Ma (Rb-Sr, metamorphic) and 3300 Ma based on U-Pb method on zircon separates. The metasediments occur as bands 10 to 100 metres thick and over 2 Kms long continuously at places within the gneisses. The bands have been intensely deformed and primary structures are generally not preserved. The striking feature of this association are its thinness, abrupt lateral variation and repetition. Another significant feature is the local presence of thin spessartine garnet rich mangan-horizons between carbonate and BIF units. These sediments thus have all the characteristics of continental marginal basin affinity. Amphibolites, interbanded with the metasediments represent original basaltic intrusives or extrusives. No unequivocal evidences like pillow structures have been found. The Sargur supracrustals are best exposed in the region between Sargur and Terakanambi, south of Mysore city (see field guide).

Quartzites are essentially orthoquartzites, however every gradation between this and pelites can be seen in the field, in the form kyanite/sillimanite-garnet and fuchsite bearing quartzites. Often paragonite containing appreciable Cr_2O_3(1.3%) representing altered kyanite/sillimanite is also seen. Some of the quartzites have abundant rutile and zircons. BIF horizons contain grunerite,orthopyroxene,-garnet, scarce hornblende and biotite in addition to magnetite and quartz. Pelites are represented by sillimanite, kyanite, corundum and graphite. Paragneisses contain sillimanite, garnet, biotite and feldspars. At places, pelites have zircon and rutile as accessories. Mn-horizons which are seen only locally contain spessartine rich garnet, clinopyroxene and quartz. Carbonates are represented by calc-silicate rocks having assemblages calcite, dolomite, calcic plagioclase, scapolite, diopside, hornblende, phlogophite and sphene.

The trace and rare earth element chemistry of the Sargur metasediments show, in general, marked similarity to the Archaean sediments. The significant departures are in the nickel and chromium abundances. The REE data of the Sargur pelites of the Terakanambi region represented by Silli-gt-bio-feldspar schists and paragneisses show LREE enrichment and flat to enriched HREE pattern. Sillimanite bearing pelites (N1, N5) have overall REE abundance and show negative Eu anamoly. The REE pattern of samples (N_{2-4}) are similar to the Archaean pelites, particularly to those of Isuas and Malenas of Western Greenland. Nil to slight Eu depletion is again typical of Archaean sediments. Highly enriched HREE pattern of N5 can be attributed to abundant zircons in the minerology. The Sargur pelites have generally lower concentrations of ferromagnesian elements and higher abundances of incompatible trace elements such as LREE, Zr and Th, resulting in higher ratios of La_N/Yb_N(av. 6.09); Th/Sc (av. 1.44) and La/Sc (av. 2.92). Chromium content of the pelites vary from 450 to 100 ppm and nickel from 180 to about 30 ppm.

Banded iron formations have very low REE abundance. They show slightly enriched LREE and flat to depleted HREE pattern. Eu is anamolous with slight enrichment and this is in contrast to marginal depletion to enrichment pattern of Proterozoic iron formations. Presence of positive Eu anamoly in Sargur BIF indicate oxidising environment. Eu/Sm ratios vary from 0.38 to 0.91, typical of Archaean BIF values.

REE abundance in the Mn-horizons is comparable to that of the Archaean sediments. Mn-horizons show enriched LREE and flat HREE with anamolous Eu. REE patterns of these bands is well evolved and has similarities with PAAS.

Amphibolites of the Sargur terrain are mostly low potassic tholeiites of oceanic affinities. This is in contrast to the Dharwar volcanics, which have continental tholeiitic character. Amphibolites generally exhibit a less fractionated REE pattern (La_N/Yb_N = 1.19), except for sample N26 (La_N/Yb_N = 3.6).

THE GEOLOGY AND PETROGENESIS OF THE SOUTHERN CLOSEPET GRANITE

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The Archaean Closepet Granite (~ 2500 Ma) is a Polyphase body intruding the Peninsular Gneiss Complex and the associated supracrustal rocks. The granite out-crop runs for nearly 500 km with an approximate width of 20-25 km and cut across the regional metamorphic structure passing from granulite facies in the South and green schist facies in the north. In the amphibolite-granulite facies transition zone the granite is intimatly mixed with migmatites and charnockite. Field observations suggests that anatexis of Peninsular gneisses led to the formation of granite melt, and there is a space relationship between migmatite formation, charnockite development and production and emplacement of granite magma.

Based on texture and cross cutting relationships four major granite phases are recognised. Relationships are not consistant from quarry to quarry, however, there is a general evolutionary trend ranging from an early granodiorite to late granite. The chronological sequence of emplacement of major granite phases are as follows

1. Pyroxene bearing dark grey granite
2. Porphyritec granite
3. Equigranular grey granite
4. Equigranular pink granite

Additionally there are small areas of 'K' and 'Na' rich rocks such as brick red rocks (9.7% K_2O) and albitite (11.6% Na_2O). Field and geochemical features suggests that they could only have arisen by extensive metasomatism.

The granite is medium to coarse grained and exhibit hypidiomorphic granular to porphyritic texture. The modal composition varies from granite granodiorite to quartz monzonite. Where the order of crystallization is deduced, biotite generally forms an early phase in the melt followed by plagioclase and quartz or quartz followed by plagioclase. Though K-feldspar generally a late phase begin to crystallize, still there was sufficient space for it to crystallize as subhedral phenocrysts. Amphibole is also an important mafic phase which is quite unstable breaking down in to biotite symplectites. Textural evidence suggests that part of the amphibole crystallized from the melt

Clinopyroxene occurs only in dark grey granite, where it is interstitial to late phase and textural evidence supports primary igneous origin. The accessories such as zircon may be derived and apatite, allanite and sphene are the early phases in the melt.

Geochemical variation of the granite suite is consistant with either fractional crystallization or partial melting, but in both the cases biotite + feldspar must be involved as fractionating or residual phases during melting to account trace element chemistry. The trace element data has been plotted on discriminant diagrams, where majority of samples plot in volconic arc and within plate, tectonic environments. However, field observations suggest a within plate environment likely to have prevailed during the evolution of the granite. When the calculated mesonormative minerologies (qtz-plag-k-feld) are plotted on phase diagrams, they suggest the derivation of granite by equilibrium fusion (batch melting) of the Peninsular gneisses. A quantitative trace element modelling has been tested. The trace element modelling suggests that partial melting to certain extent fractional crystallization were in operation during the evolution of the granite suite.

The granite show distinct REE patterns with variable total REE content. Textural evidence argues that large fraction of REE resides in accessory phases such as zircon, apatite, allanite and sphene. The REE abundances observed indicate no evidence for progressively more fractionated REE patterns from granodiorite to granite. The dark grey granite contains high total REE and show coherent patterns without any significant Eu anomalies. The Porphyritic pink granite exhibits variable total REE and fractionated patterns without any significant Eu anomalies. The porphyritic grey and equigranular grey granite with variable total REE show HREE enrichment, and negative Eu anomalies. The equigranular pink granite with variable total REE show slight LREE enrichment and negligible Eu anomalies. The REE patterns and overall abundances suggests that the granite suite represents a product of partial melting of crustal source in which fractional crystallization operated in a limited number of cases.

LATE ARCHEAN GREENSTONE TECTONICS -- EVIDENCE FOR THERMAL AND THRUST-LOADING LITHOSPHERIC SUBSIDENCE FROM STRATIGRAPHIC SECTIONS IN THE SLAVE PROVINCE, CANADA; W.S.F. Kidd, Dept. Geol. Sci., SUNYA, Albany, NY 12222, USA, T.M. Kusky, Dept. Earth Sci., Johns Hopkins Univ., Baltimore, MD 21218, USA, D.C. Bradley, LDGO, Palisades, NY 10964, USA

Subsidence in rifts and passive continental margins is driven by stretching and subsequent cooling and thickening of the lithosphere(1); subsidence in foreland trough basins is a result of thrust-loading and flexure of the lithosphere(2). Sediment sequences localized by these different mechanisms have distinctive sequences of facies and are one of the more convincing forms of evidence for the operation of plate tectonics in the Palaeozoic and Proterozoic. Archean examples of such sequences have not been so obvious, perhaps because none are preserved in little deformed state, and the most likely candidates on the basis of lithological assemblages for passive margin sequences (3,4) are not only highly deformed and structurally dismembered but are also strongly metamorphosed. We have identified intact stratigraphic sections of passive margin type, and others of foreland trough-type in deformed but low-grade Archean rocks in several extremely well-exposed areas of the Slave Province, N.W.T., Canada. These sequences are similar in most respects to younger examples and support the hypothesis (5,6,7) that tectonic processes similar to those operating now were active in the Archean.

On both the north and south arms of Point Lake an intact stratigraphic sequence above a thick conglomerate containing shallow-water arenites and intercalated mafic and felsic volcaniclastics and volcanics starts with a unit of black pyritiferous slate and argillite of 60-200 m present thickness. This contains a minor proportion of siderite iron formation, calcarenite-siltite and limestone breccia beds and, adjacent to the volcanics at the base, local quartzose and tuffaceous silts and arenites. These black slates are conformably succeeded by a thick sequence of quartzofeldspathic turbidite greywackes and pelites, with local magnetite iron formation in some of the pelitic intervals. The turbidites coarsen and thicken upward through the basal 20-100 m. The overall sequence of turbidites is several km thick and is imbricated by thrusts directed westwards. We interpret this sequence to be the product of submarine thrust-loading subsidence, with the black slates being the outer trench slope deposits and the turbidites the trench floor deposits, subsequently incorporated into an accretionary thrust stack.

Sections in the Cameron River belt, in the area of Upper Ross Lake-Victory Lake-Detour Lake, lie with observed unconformity on tonalitic gneisses. At Detour Lake, deformed but low grade sediments consisting largely of quartz and carbonate arenites, with a basal biotite phyllite matrix conglomerate and a local upper unit of calcsilicates and marbles, form a section about 500 m thick. Similar sediments are much thinner nearby, along strike, but 500 m of quartzites in the same tectonic position are reported (8) in the Beaulieu River region farther north. These shallow water sediments, which we interpret as a passive margin sequence, are truncated by a major thrust carrying greenstone belt lithologies generally southwestward, except near Detour Lake, where the section passes up through a 100 m thick interval of pelite and iron formation to a quartzofelspathic turbidite sequence, of overall great thickness, and probably cut by many thrusts. This change to turbidite deposition we also interpret as the development of a submarine foreland-basin caused by thrust-loading.

Sequences like these are not unique to the Slave Province but the recognition of their significance depends on good outcrop and being able to identify which contacts are stratigraphic and which are important faults. Similar passive margin-type sequences are well documented from Zimbabwe (9) and the Superior Province (10); in both cases the sediments lie unconformably on older basement and are only a maximum of a hundred to a few hundred meters thick. We interpret adjacent volcanics, including komatiites in Zimbabwe, to be in tectonic contact with the sediments, as they are observed to be in the Slave Province. Within the Archean, the Witwatersrand basin has been suggested to be a foreland basin due to thrust-loading subsidence (11); within Archean greenstone belts, the only documented thrust-loading subsidence sequence is that of the Barberton Mtn Land (12); they are probably common, and several potential examples, which we have not yet had the opportunity to examine, occur elsewhere in the Slave Province (data in 13). The change between the Bababudan and Chitradurga Groups (14) of southern India, and much of the sedimentation in the Chitradurga Group, is possibly of the same origin.

The thrust-subsidence sequences in the Slave Province are very similar in facies and thickness to Phanerozoic examples, particularly those from places where island arc terranes dominate, for example central Newfoundland (15). The combined effect of lithospheric thickness and the size of the load provided by the thrust stack must therefore have resembled the same combination of these two factors in more recent times. In contrast, the passive margin sequences, while of very similar lithologies in similar order to those in younger examples, are consistently thin in comparison with them, even allowing for thickness reduction by ductile strain. This difference can be interpreted in at least two different ways; one is that a higher mantle heat production caused slower lithospheric thickening and a smaller total equilibrium thickness after a rifting event, resulting in less overall thermal subsidence of rifted margins. Another is that rifted margins were more swiftly incorporated into convergent tectonic systems than in later times. Unless independent evidence on lithospheric thickness can be obtained from other aspects of the Archean record or these sequences can be much more precisely dated than at present, it may prove difficult to distinguish between these possibilities. This evidence does show, however, that tectonic processes active in the Archean had primary effects on the lithosphere indistinguishable from those of present plate tectonics.

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CHARACTERIZATION OF FLUIDS INVOLVED IN THE GNEISS-CHARNOCKITE TRANSFORMATION IN SOUTHERN KERALA (INDIA)

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Most impressive examples of 'in-situ' charnockitization occur in the Proterozoic crustal segment south of the Achankovil shear belt (Pon Mudi unit (1)), where migmatic garnet-biotite gneisses have been partially converted to coarse-grained charnockite s.str. along a system of conjugate fractures about 550 m.y. ago. To characterise the composition of pore fluids and to understand their role in the process of 'in-situ' charnockite formation, fluid inclusions in spatially related gneisses and charnockites were studied by microthermometry, Raman-Laser-Probe analysis and mass spectrometry (2). $\delta^{13}C$ data on graphite (this work and (3)) and fluid inclusions in quartz (4) as well as $\delta^{18}O$ whole rock data provided important information on the origin of the fluids.

The fluid inclusion characteristics of the gneisses and associated charnockites are similar and reveal a comparable and complex evolution of the pore fluids. Rare briny inclusions (+ salt) are considered to represent relics of early metamorphic fluids which survived high-grade regional metamorphism and subsequent charnockitization. The common type of fluid inclusions are medium- to low-density carbonic inclusions (Th: +15 to +27 ^{o}C Tm: -60.0 to -56.6 ^{o}C; ρ 0.70-0.86 g/cm^3) which occur in several sets of healed fractures. The microthermometric data indicate partial to complete physical equilibration of these fluids by progressive leakage and repeated reentrapment as a consequence of near-isothermal uplift of the rock complex. The carbonic fluids contain up to 14 mol% of nitrogen but less 1 mol% hydrocarbons (CH_4 and C_2H_6). Nitrogen inclusions (Th -152 to -130 ^{o}C; up to 16 mol% hydrocarbons, nil carbon dioxide) commonly occur in both the gneisses and charnockites and at several localities predominate. A generation of these fluids by devolatilization of NH_4-bearing K-feldspar and biotite is likely. The presence of nitrogen and graphite ($\delta^{13}C$ -15 to -20 per mil) in the gneisses and charnockites points to the sedimentary nature of the protoliths. Medium-density watery inclusions of low salinity (ρ 0.89 - 0.94 g/cm^3; < 4 mol% equiv. NaCl) are the texturally latest entrapped metamorphic pore fluids. Where they cross trails of carbonic inclusions, mixed H_2O-CO_2 inclusions (forming clathrate ices) developed. Bulk fluid analysis by mass spectrometry on quartz concentrates showed the charnockites to be higher in N_2, CH_4 and H_2O but lower in H_2 in comparison to the gneisses. CO_2 and Ar have similar abundances in both rock types.

The fluid inclusion characteristics suggest that the composition of metamorphic pore fluids involved in high-grade regional metamorphism and subsequent charnockitization can be modelled by graphite-fluid equilibria in the C-O-H-N system. Accordingly, the pore fluids in the gneisses and charnockites were internally buffered towards strongly water deficient and reduced compositions. Oxygen fugacities close or lower than defined by the QFM buffer are in accordance with the silicate-opaque mineral assemblages and mineral chemistry data (1,7).

Further evidence for an internal generation and buffering of the pore fluids comes from the $\delta^{13}C$ data on graphite and carbonic fluid inclusions: Graphite from typical garnet-biotite-(sill, cord) gneisses exhibit $\delta^{13}C$ values between -14‰ and -17‰ (see also (3)) and obviously was derived from the degradation of organic matter (-20‰ to -35‰ ; data for kerogen). Reported $\delta^{13}C$ values for carbon dioxide trapped in the fluid inclusions of comparable gneiss samples vary between -10‰ and -15‰ (4). The difference in the $\delta^{13}C$ values of graphite and carbonic fluids (5 to 7‰), in agreement with the experimental fractionation data for the graphite-CO_2 system (5), indicates attainment of isotopic equilibrium near peak metamorphic temperatures (< 700 ^{o}C). Graphite and carbonic fluids in coarse-grained massive 'incipient' charnockites show similar $\delta^{13}C$ systematics. The graphites are isotopically lighter (-19‰ ; -22‰) than the carbonic fluids (-7‰ to -15‰ ; data reported in (4)). Graphite of one charnockite sample, however, has a $\delta^{13}C$ value of -12‰ , much similar to the values obtained for graphite (-10‰ to -13‰ this work and (3)) from garnet and cordierite-bearing pegmatites which cut across the gneisses but are older than the charnockites. The data could indicate that graphites in these samples crystallised from isotopically heavier carbonic fluids (< -5‰). A meaningful interpretation, however, is not possible unless $\delta^{13}C$ data on the associated fluids are available.

A detailed study of oxygen isotopes was carried out on one typical exposure of 'in-situ' charnockitization (Kottavattam). Gneisses and associated charnockites exhibit identical $\delta^{18}O$ values of 10.3 ‰ which are typical of psammo-pelitic metasediments. This findings provide further evidence on the internal nature of carbonic fluids. Influx of carbonic fluids with mantle isotopic signature ($\delta^{18}O \sim 8$) would have shifted the charnockite $\delta^{18}O$ to lower values.

In the light of the fluid inclusion and stable isotope data it thus appears unlikely that charnockitization in southern Kerala was caused by the influx of externally derived carbonic fluids and the concommitant decrease in water activity as suggested by the proponents of the CO_2-streaming hypothesis (6). An alternative mechanism has been recently proposed for 'in-situ' charnockitization in southern Kerala (1) and is discussed in an other contribution to the workshop (7).

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U-Pb AGES AND Sr, Pb AND Nd ISOTOPE DATA FOR GNEISSES NEAR THE KOLAR SCHIST BELT: EVIDENCE FOR THE JUXTAPOSITION OF DISCRETE ARCHEAN TERRANES; E.J. KROGSTAD[1], G.N. HANSON[1], and V. RAJAMANI[2]
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Two Archean gneiss terranes in the Karnataka Craton of South India are separated by the narrow (3-8 km wide) Kolar Schist Belt, a zone of strong shearing. The largely granodioritic terranes have distinct U/Pb, Sm/Nd and Rb/Sr histories. Ages of plutonic rocks in the two terranes show minor differences, which are resolvable by U-Pb dating of small samples of zircon and of cores of single zircons, which have uncertainties of less than 10 Ma. The Kambha Gneiss, which is the major unit east of the Kolar Schist Belt has a U-Pb zircon age of 2532 Ma (Table 1). West of the belt, the granodioritic Dod Gneiss was emplaced at 2633 Ma (Table 1). This gneiss unit has inherited zircon cores which are older than 2800 Ma. The granodioritic Dosa Gneiss has an apparent magmatic age of 2613 Ma (Table 1). The Patna Granite, which is exposed north of the Kolar Gold Fields area, has a concordant zircon age of 2551 Ma.

Sphene U-Pb ages, perhaps indicating the time of cooling from igneous or high grade metamorphic events, are 2521 Ma east of the schist belt and 2553 Ma west of the Belt. This age difference for adjacent gneiss terranes suggests that the terranes had separate histories until after 2520 Ma.

The Sm/Nd, Rb/Sr and U/Th/Pb histories of these two granodioritic gneiss terranes are also quite different. East of the Schist Belt 2530 Ma gneisses have initial Nd, Sr and model initial Pb ratios (Table 1) which are consistent with derivation from a source with limited, if any, crustal history. On an epsilon Sr - epsilon Nd diagram (Fig. 1), these gneiss samples lie along a steep negative slope similar to data from: a) rocks derived from present day subcontinental mantle; or b) mixing of melts derived from depleted mantle with those from a long-term, low Sm/Nd and low Rb/Sr reservoir, such as the lower crust. The Pb data do not, however, indicate that one of the sources of the Kambha Gneiss is an old, low U/Pb, high Th/U reservoir such as lower crust. These primitive initial Nd, Sr and Pb ratios allow only a short-lived crustal history for the sources of these gneisses east of the Schist Belt. These constraints contrast with some models for the evolution of the Dharwar craton which suggest that no new crust was formed after 3000 Ma.

West of the Kolar Schist Belt the chemically primitive 2633 Ma Dod Gneiss has Nd, Sr and model Pb initial ratios (Table 1) which range from mantle-like to those showing evidence of a crustal influence. The 2613 Ma Dosa Gneiss which occurs in the same area has initial Nd, Sr and model initial Pb ratios (Table 1) which show a stronger crustal influence than those of the Dod Gneiss. K-feldspar Pb data from samples of the Dod and Dosa gneisses and the 2551 Ma Patna Granite lie along a correlation line with a slope age of 3200 to 2600 Ma, with a lower intercept with a model mantle ($u_1 = 8.0$) at 2600 Ma (Fig 2). On an epsilon Sr - epsilon Nd diagram (Fig. 1), data from the Dod and Dosa gneisses lie along a line with a slope much more shallow than that for the Kambha Gneiss samples. These data suggest that the magmatic precursors of these gneisses included mixtures of material derived from mantle sources depleted in incompatible elements and significantly older upper crustal material.

One possible candidate for the source of the crustal contaminant is the source of a felsic rock which is found as a pod-like body in the shear zone west of the schist belt. This sample has K-feldspar with extremely radiogenic Pb, and has very radiogenic Sr, and unradiogenic Nd (Banded Gneiss, Table 1). Zircon cores from this rock include an inherited component older than 3170 Ma. Another possible contaminant is represented by a granitoid inclusion from a inclusion-rich horizon of the Champion Gneiss. This rock has discordant zircons which have minimum ages of 2900 Ma. This rock has also very evolved K-feldspar Pb and unradiogenic Nd (Champion Inclusion, Table 1). The K-feldspar Pb compositions of these two samples lie on, or near, the 3200 to 2600 Ma line fitting the Dod and Dosa gneiss K-feldspar data (Fig. 2). These data suggest that these felsic samples may be fragments of an evolved, older, continental crust which is apparently absent immediately east of the belt.

Assuming that the juxtaposition of the terrannes was accompanied by a metamorphic event affecting the belt and the gneisses on both sides of the belt, because the sphenes from either side give different U-Pb ages the metamorphism was not intense enough to similarly reset the sphene ages on both sides. Thus the juxtaposition of the terranes probably postdated the sphene (cooling) age of the eastern Kambha Gneiss (2521 Ma). K-feldspar - whole rock Pb-Pb ages, which have closure temperatures less than that for sphene, range from 2450 to 2300 for samples on both sides of the belt. These ages are similar to the 2420 ± 12 Ma $^{40}Ar/^{39}Ar$ plateau age on muscovite from a sample from the western shear zone, which is the age (or a minimum age) for the time of shearing of the gneisses, which occurred after the terranes were juxtaposed.

TABLE 1

unit	zircon age (Ma)	sphene age (Ma)	epsilon Sr	epsilon Nd	source model mu(1)
WEST					
Dod Gneiss	2633 (+/-8)	2553 (+/-2)	+19, +30	+1.7 to -1.0	8.7 to 9.2
Dosa Gneiss	2613 (+/-10)		+40. +45	-1.0 to -3.5	8.7 to 9.2
Patna Granite	2551 (+/-2.5)	2553 (+/-2)			10
POSSIBLE WEST BASEMENT					
Banded Gneiss	>3170		+318 (at 2600 Ma)	-4.5 (at 2600 Ma)	~35 (3200-2600 Ma)
Inclusion, Champion Gn.	>2900			-7.5 (at 2600 Ma)	~15 (3200-2600 Ma)
EAST					
Kambha Gneiss	2532 (+/-3)	2521 (+/-2) 2514	-2 to -4	+4.5 to 0.0	8.0 to 8.2

U-Pb AGES AND Sr, Pb AND Nd ISOTOPE DATA FOR KOLAR GNEISSES
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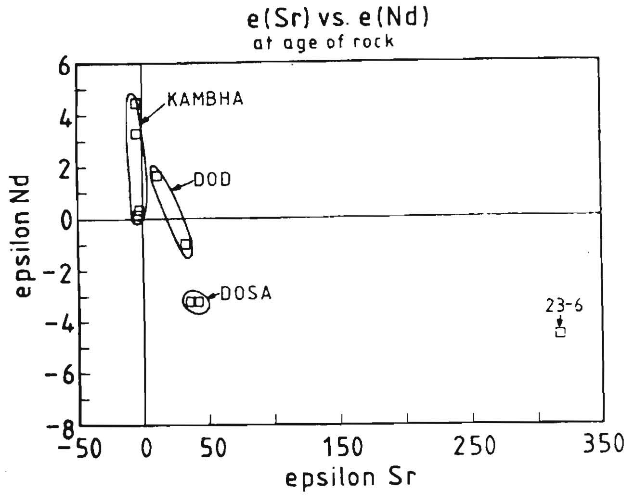

Figure 1. Epsilon Sr versus epsilon Nd diagram showing samples from the Kambha Gneiss at 2530 Ma and the Dod and Dosa gneisses at 2600 Ma. Also shown is the Banded Gneiss sample (23-6) from the shear zone on the western side of the schist belt. The eastern samples lie in the field of depleted mantle, with a steep slope which does not suggest contamination by an old, high Rb/Sr crust. The western samples range from similar values of epsilon Nd to points which suggest that an older, high Rb/Sr and low Sm/Nd crust was among their sources. The Banded Gneiss sample may represent part of such an older crust.

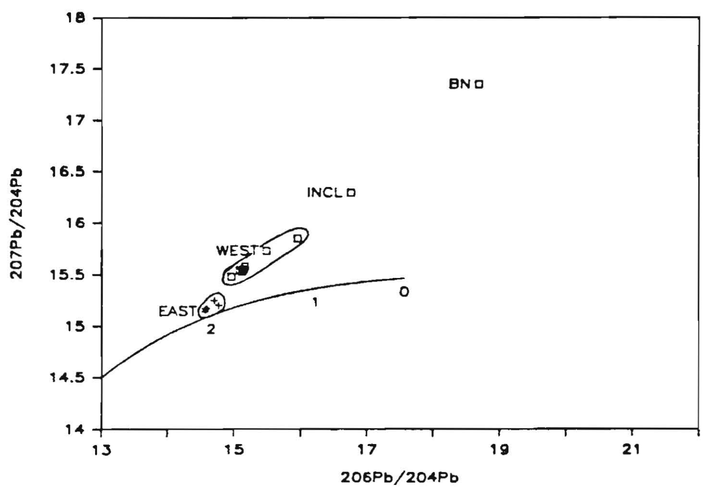

Figure 2. Pb isotopic composition of residues of leached K-feldspars from the major gneiss units. Kambha Gneiss samples lie in a restricted field with low $^{207}Pb/^{204}Pb$ values, consistent with a lack of significantly older crust on the east side of the schist belt. Samples from the west side of the belt lie along a line with a steep, positive slope which can be interpreted as a mixing line between old, crustal Pb, represented by the Banded Gneiss ("BN") and Champion Gneiss Inclusion ("INCL") points, and a more primitive, "mantle-like", Pb composition. The slope of this line has an age of 3200-2600 Ma.

ACCRETION OF THE ARCHEAN SLAVE PROVINCE

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The Slave Province is an Archean "granite-greenstone" terrane located in the northwestern portion of the Canadian Shield. Its history spans the interval from 3.5 Ga, the age of 'old gray gneisses' exposed in an anticlinal culmination in the Wopmay Orogen, to 2.6 - 2.5 Ga, the age of major granitic plutonism throughout the province. Most of the volcanic and sedimentary rocks formed in the 2.7 - 2.6 Ga interval. Traditional tectonic models for the Slave treat the Province as one recording continental extension, with the volcanics and sediments filling normal fault bounded linear troughs developed on pre-existing sialic crust (eg., 1-6). Hoffman (7,8) and Kusky (9,10,11) have recently pointed out major problems with applying a continental rift model to the Slave Province. The regional geology is described here in the light of a collisional tectonic model in which different belts in the province are regarded as accreted terranes whose suturing formed the Archean Slave Province. Although the model is preliminary and largely speculative, it explains many aspects of the geology of the province that are ignored or contradicted by the continental rift model, and it serves as a testable hypothesis on which future field efforts may be focused.

Figure 1 is a cartoon terrane map of the Slave Province; it was constructed by first taking lithological maps of the province (2, 12, 13), graphically removing relatively young granitic intrusive rocks, and then extrapolating contacts between regions that have not been removed by granites. Field work in the 1985, 1986, and 1987 seasons concentrated on determining the nature of terrane boundaries (particularly in the western and central terranes), kinematics of major movement zones, and characterizing rock suites of different terranes. Extrapolation was aided by SEASAT orbital radar images processed in the Laboratory for Terrestrial Physics at NASA's Goddard Space Flight Center and by maps prepared by the Geological Survey of Canada and the Geology Division of the Department of Indian and Northern Affairs, Canada. On the terrane map the Slave is divided into four major tectonic zones with different characteristics and ages; from west to east these are here named the Anton Terrane, the Sleepy Dragon Terrane, The Contwoyto Terrane, and the Hackett River Terrane. The characteristics of and differences between the terranes is discussed in more detail elsewhere (14).

The Anton Terrane stretches from Yellowknife in the southern portion of the province to Anialiak River in the north (Figure 1), and it hosts some of the oldest ages reported from the Slave Province. Included is a 3.48 Ga tonalitic gneiss exposed in an anticlinal culmination in the Wopmay Orogen west of Point Lake (S. Bowring, pers. comm.), and a 3.1 Ga age on granitoid rocks from a diatreme near Yellowknife (15). Quartzofeldspathic gneisses are widely distributed throughout the Anton Terrane, and these are worthy of intensive geochronologic studies to determine if even older rocks are present. To the northwest of Yellowknife and southwest of Point Lake a series of mafic volcanic and metasedimentary rocks are preserved; their relationships to surrounding rocks are not clearly understood, although a similar suite of rocks immediately southwest of Point Lake is bounded on all sides by mylonites and is clearly a klippe. The Anton Terrane is interpreted as the remnants of an older Archean continent or microcontinent.

The Sleepy Dragon Terrane includes quartzofeldspathic gneissic complexes such as the 2.8-2.7 Ga Sleepy Dragon Complex in the south, and a 3.1 Ga chloritic granite on Point Lake. The gneisses are locally

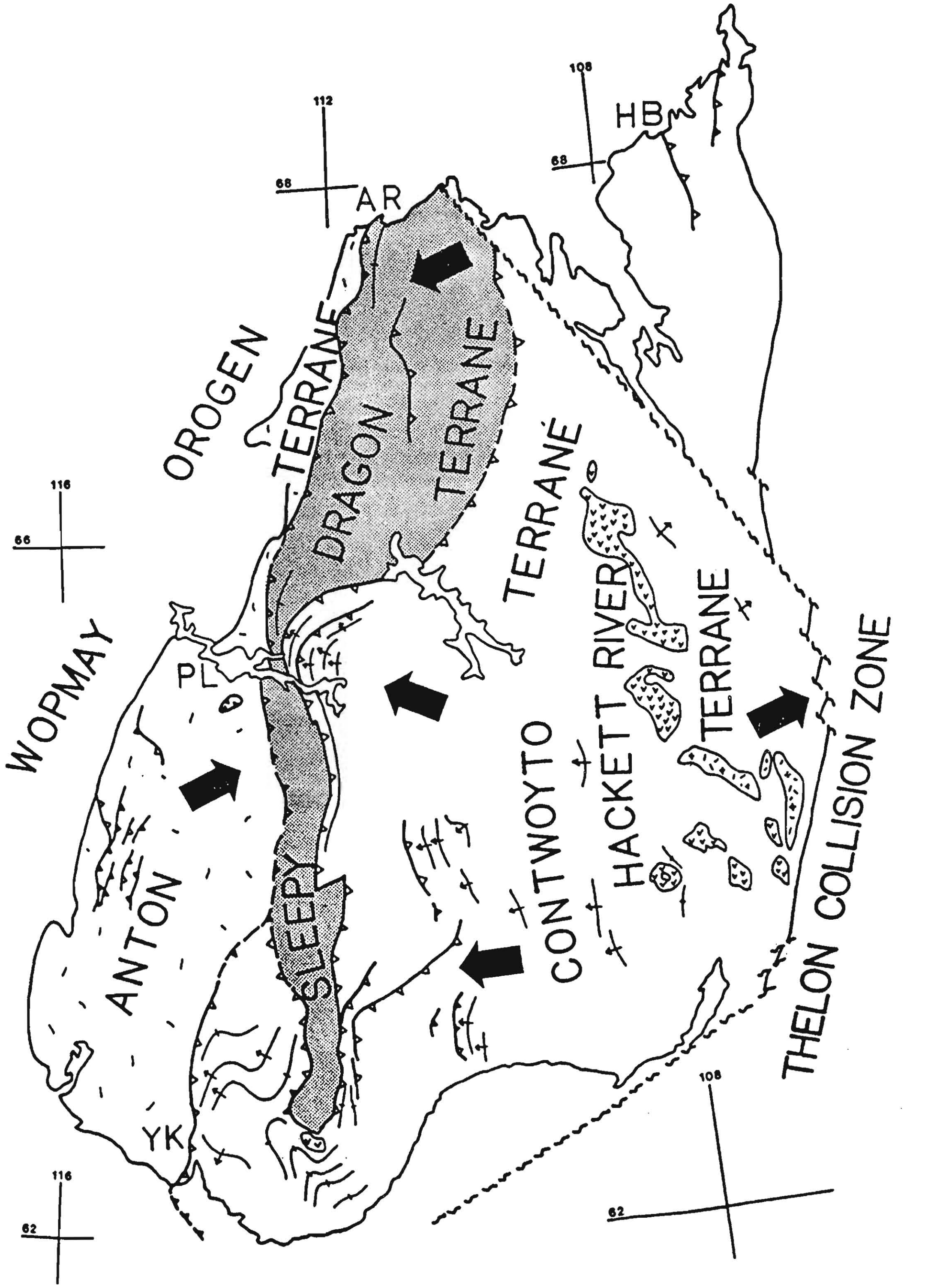

Figure 1. Terrane map of the Slave province with young granitic rocks removed. Bold arrows indicate approximate transport directions, thin lines with arrows show fold axial planes and vergence. YK = Yellowknife, PL = Point Lake, AR = Anialiak River, HB = Hope Bay.

overlain by shallow water sedimentary sequences with strong affinities to Phanerozoic passive margin sequences (19). The gneisses together with mafic greenstone belts of oceanic affinity (11) are presently disposed in a westward verging fold and thrust belt. The Sleepy Dragon Terrane could thus simply be an imbricated and westward transported section of the Anton Terrane, or it could be a separate accreted microcontinent.

Rocks of the Contwoyto Terrane consist almost entirely of graywacke turbidites (disregarding the intrusive granites), disposed in a series of westward verging folds and thrusts (15,16). At Point Lake these grade down into a flexural loading sequence related to westward directed thrusting (19). Greenstone belts within the accretionary complex are interpreted as oceanic material scraped off an eastward dipping subduction zone.

The Hackett River Terrane consists of a series of northwest striking intermediate, felsic and mafic volcanic belts along with some granitic and gneissic rocks in the south. Caldera complexes and transitions from subaerial to subaqueous volcanic deposits are locally preserved (15). These volcanic belts differ significantly from greenstone belts to the west which consist primarily of mafic volcanic and plutonic rocks (12). The Hackett River Terrane is interpreted as an island arc formed above an east dipping subduction zone, with the Contwoyto Terrane representing an accretionary complex located in the forearc position.

The formation of the Slave Province can thus be simply explained by an island arc (Hackett River Terrane) and forearc accretionary prism (Contwoyto Terrane) moving westward above an east dipping subduction zone, which collided with and partially overrode an older continent (Anton Terrane).

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ANORTHOSITES AND ALKALINE ROCKS FROM THE DEEP CRUST OF PENINSULAR INDIA C.Leelanandam, J.Ratnakar, and M.Narsimha Reddy, Department of Geology, Osmania University, Hyderabad- - 500 007, INDIA.

Anorthosites and alkaline rocks are potentially useful as geochemical probes of their mantle sources at very early to early periods of the evolutionary history of the Earth's crust. There are about forty anorthosite and an equal number of alkaline rock occurrences in the Precambrian shield of Peninsular India (Figs. 1 & 2), and a great majority of them are virtually restricted to the Eastern Ghat mobile (granulite) belt which is comparable to the Grenville province of Canada.

The Archaean and Proterozoic anorthosite complexes cover a total area of over 1300 km^2. Among the Archaean anorthosite complexes, the Chimalpahad (1) complex ($\sim$200 km^2) is similar in certain respects to the Sittampundi (2) complex (7-12 kb; 675-850°C). Some of the Proterozoic anorthosite massifs which are geographically very far away exhibit remarkable similarities; the Bankura (3,4) and Bolangir (5) massifs were equilibrated at metamorphic temperatures ($\sim$650°C) and pressures ($\sim$6kb) corresponding to depths of 15-25 km, while that of Oddanchatram (6) was equilibrated at a higher temperature (980 ± 20°C) and lower pressure($\sim$ 5.3 kb).

The alkaline plutons covering a total area of $\sim$450 km^2 have diverse lithologies and variable rock associations. Rocks with 50-65% SiO_2 (nepheline syenites and syenites) are abundant, while those with 65-70% SiO_2 (quartz syenites and alkali granites) are less abundant; carbonatites and ocellar lamprophyres (camptonites and sannaites) are conspicuous, though insignificant, members of some alkaline plutons. Most of the nepheline syenites are miaskitic (7) and are of igneous origin (700-880°C). The undersaturated and oversaturated syenites are supposed to have formed from a critically undersaturated hornblende syenitic magma by a branching differentiation mechanism from an originally hydrous alkaline basalt magma as at Purimetla (8) in the Prakasam province (9), east of the Cuddapah basin (Fig.1).

The charnockitic (gneiss-granulite) region of Peninsular India is uplifted as a whole relative to the non-charnockitic (granite-greenstone) region and Fermor's line (10) forms an abrupt discontinuity between contrasting geologic terrains. The metamorphic discontinuity across the boundary between the Eastern Ghats and the adjoining craton, as at the eastern margin of the Cuddapah basin (11-13), suggests thrusting of the eastern terrain (deeper crustal levels) over the western terrain (shallower levels). The boundary (comparable to the Grenville Front) is marked by the presence of an east dipping thrust zone (see the inset map of Fig.1) separating the younger crustal blocks of the Eastern Ghat province from the older blocks of the craton (14). Models invoking collision tectonics with attendant anomalous crustal thickening of the Proterozoic mobile belt and with high thermal gradients may explain the anorthosite genesis. The granulite terrains subsequently developed very low thermal gradients and experienced the alkaline magmatism signifying very deep melting in middle-late Proterozoic times (15). The faults and deep fractures in the thickened and shortened continental crust passively allowed the emplacement of post-orogenic alkaline plutons. There is no perceptible clustering

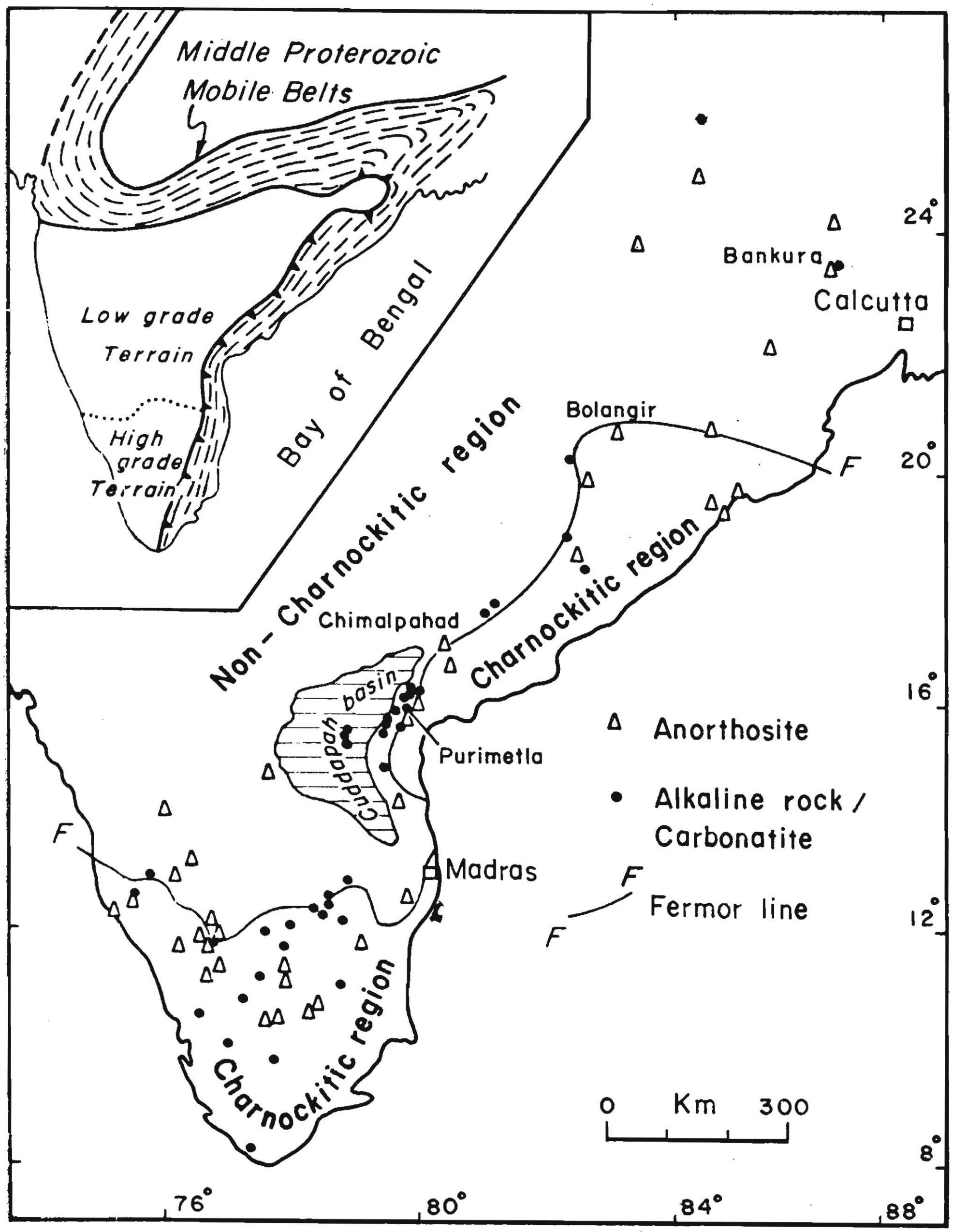

Fig.1

of either anorthosite or alkaline plutons in the Proterozoic shear zones in south India (Fig.2), though the plutons are almost confined to the Proterozoic mobile belt representing deep crust of Peninsular India.

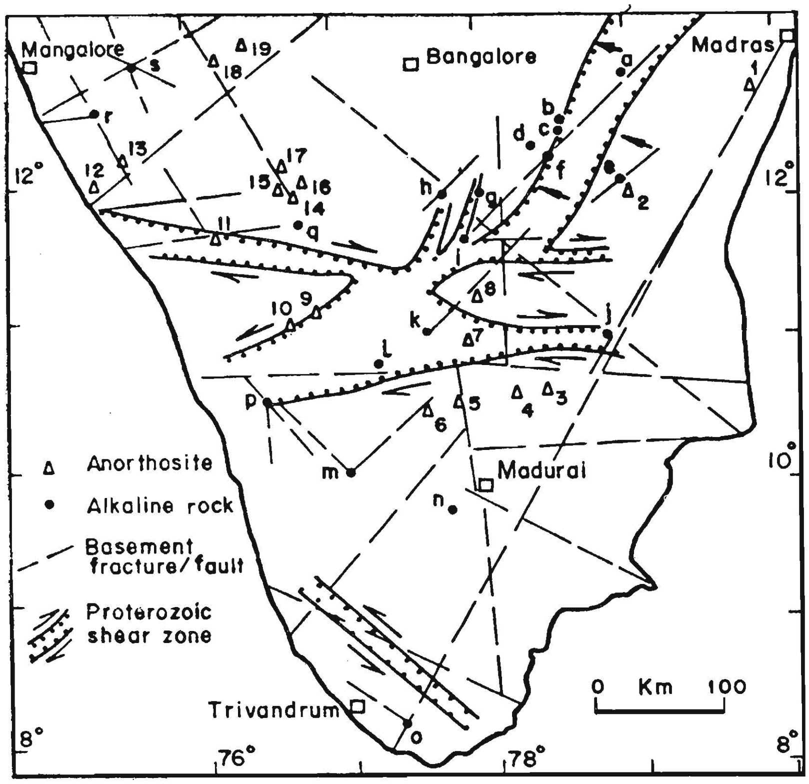

Fig.2

Anorthosites: 1.Chinglepet, 2.Mamandur, 3.Manapparai, 4.Kadavur,5.Oddanchatram, 6.Palni, 7.Chinnadharapuram, 8.Sittampundi, 9.Togamalai, 10.Attapadi, 11.Kabbani, 12.Perinthatta, 13.Kottanjariparambu, 14.Gundlupet,15.Hullahalli, 16.Konkanhundi, 17.Sindhuvalli, 18.Holenarasipur, 19.Nuggihalli. Alkaline rocks: **a.**Paravamalai, **b.**Elagiri, **c.**Koratti, **d.**Sampalpatti, **e.**Torapaddi, **f.**Sevattur, **g.**Piccili, **h.**Hogenkal, **i.**Pakkanadu, **j.**Ariyalur, **k.**Sivamalai, **l.**Kundurubetta, **m.**Munnar, **n.**Kammam mettu, **o.**Puttetti, **p.**Mannapra, **q.**Sholayar, **r.**Sullia, **s.**Peralimala.

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DEEP CRUSTAL DEFORMATION BY SHEATH FOLDING IN THE ADIRONDACK MTS., U.S.A.

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As described by McLelland and Isachsen[1], the southern half of the Adirondacks are underlain by major isoclinal (F_1) and open-upright (F_2) folds whose axes are parallel, trend approx. E-W, and plunge gently about the horizontal. These large structures (50-100 km along strike) are themselves folded by open upright folds trending NNE (F_3). McLelland[2] pointed out that elongation lineations in these rocks are parallel to X of the finite strain ellipsoid developed during progressive rotational strain. These linear elements are most spectacular in ribbon gneisses consisting of quartz and feldspar ribbons up to 60 cm long, 1 cm wide, and 1-2 mm in thickness. The ribbons can be shown to evolve from progressively sheared feldspar megacrysts as well as aggregates of quartz grains, both indigenous to inequigranular granitic plutonites.

The parallelism between F_1 and F_2 fold axes and elongation lineations led McLelland[2] to hypothesize that progressive rotational strain, with a west-directed tectonic transport, rotated earlier F_1-folds into parallelism with the evolving elongation lineation. Rotation is accomplished by ductile, passive flow of F_1-axes into extremely arcuate, E-W hinges, i.e., sheath folds. F_2 folds represent either response to convergence in the ductile flow field or are the crests and troughs of large sheath folds with which they are contemporaneous.

In order to test these hypotheses a number of large folds were mapped in the eastern Adirondacks. The largest of these (McLelland and Isachsen[1]) lies just south of the Marcy anorthosite massif and is referred to as the F_2, Pharoah Mt. anticline. This anticline has a wavelength of ~ 20 km and plunges gently to the east at its eastern end. The charnockites coring the anticline may be followed for at least 50 km to the east and reappear in the Ticonderoga dome ~ 10 km to the east. On the flanks of the anticline are distinctive marbles of the Paradox Lake Formation whose contact with the charnockites gives clear expression to the anticline. As these marbles are followed north or south from the anticlinal hinge they can be traced around vertical isoclinal (F_1) fold hinges that occur on <u>both</u> flanks of the F_2 anticline. The only way for this geometry to be consistent is if the Pharoah Mt. anticline is a flattened sheath fold with horizontal hinges that are isoclinal.

Other evidence supporting the existence of sheath folds in the Adirondacks is the presence, on a map scale, of synforms whose limbs pass through the vertical and into antiforms. This type of outcrop pattern is best explained by intersecting a horizontal plane with the double curvature of sheath folds.

It is proposed that sheath folding is a common response of hot, ductile rocks to rotational strain at deep crustal levels. At shallower levels the crust responds to the same forces by developing thrust faults such as those mapped by McLelland and Isachsen[1] in the eastern Adirondacks. The development of sheath folds is probably commonplace within the high grade cores of major mobile belts. The presence of such structures should be suspected whenever well developed elongation lineations parallel early fold axes, especially when these are isoclinal. Of paramount importance are tectonic interpretations related to sheath folding, because, unless recognized as parts of sheaths, the isoclinal fold hinges may be misinterpreted as perpendicular to the long axis (X) of the finite strain ellipsoid when, actually, they are parallel to it. Thus, the recognition of sheath folds in the Adirondacks reconciles the E-W orientation of fold axes with an E-W elongation lineation. These folds appear to have formed during, or shortly prior to, peak granulite facies metamorphism at ~ 1050 Ma[3]. They fold an earlier high grade (garnet-sillimanite-K-feldspar) foliation which is believed to pre-date ~1300 Ma[3] tonalitic gneiss. Orthogneisses emplaced at 1160-1130 Ma[3] are clearly effected by the sheath folding. The Sacandaga Fm. that envelopes the Piseco anticline of the southern Adirondacks is believed to be a mylonitized migmatite envelope around the 1150 Ma[3] granitic gneiss coring the anticline. The mylonitization formed during sheath folding and ribbon lineation formation along the anticline.

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U-PB ZIRCON GEOCHRONOLOGY AND EVOLUTION OF SOME ADIRONDACK META-IGNEOUS ROCKS

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A total of 18 new U-Pb zircon ages from the anorthosite-mangerite-charnockite-granite-alaskite (AMCAL)-suite of the Adirondacks yield the following results (Chiarenzelli et al[1]):

(1) Emplacement ages of the mangeritic and charnockitic rocks are constrained in the interval 1160-1130 Ma;

(2) Hornblende granitic gneiss gives zircon ages of ~1100 Ma but cores of ~1150 Ma have been separated suggesting that 1110 Ma represents a mixed age;

(3) Migmatitic alaskitic gneiss yields ages of ~1070 Ma. Zircons are clear and unzoned in these minimum melt migmatites, suggesting that they grew during anatexis;

(4) Zircons in anorthosites are small, equant, multi-faceted, and clear similar to metamorphic zircons in mafic granulites. These zircons yield ages of ~1050 Ma and are interpreted as metamorphic with Zr exsolved from Fe, Ti-oxides and/or pyroxenes.

(5) Sphene ages in the Adirondack Highlands occur in the interval 1050-950 Ma and this is assumed to be the age of peak granulite facies metamorphism.

These results leave the age of the anorthositic rocks unresolved with the only direct determination being a Nd/Sm age of 1288±36 Ma by Ashwal and Wooden[2]. Based upon apparently mutually cross-cutting relationships, McLelland[3] interpreted the anorthositic and mangeritic/charnockitic rocks as coeval. This conclusion is consistent with the close association of these rock types on a global scale, as well as the repeated zonal envelopment of anorthositic massifs by acidic rocks. That the acidic and mafic rocks constitute a bimodal, non-comagmatic suite has been shown by McLelland and Whitney[4] on the basis of chemical data and field relationships.

The presence of xenocrysts of andesine in charnockite 10-15 km away from the nearest anorthosite indicates that the acidic rocks were largely liquid to at least these distances when they acquired the xenocrysts. Hargraves[5] and Isachsen et al.[6] have argued that the acidic rocks are older gneisses melted by the intruding anorthosite slab which, upon solidification, was intruded by the still-molten mangerites and charnockites. In order to test this hypothesis the heat flow equation was solved for a 4 km thick sill in a semi-infinite half space with grad. T = 30°C/km. A series of different initial conditions were applied, and it was found that even for the unrealistically extreme case of a totally liquid anorthosite (T=1300°C) intruding into anhydrous granitic gneiss ($T_{INITIAL}$=900°C), melting is limited to ~55% at the contact and decreases quickly to 0% at 4 km above the sill. It is clear that the initial and latent heat reservoirs of the anorthosite are insufficient to produce the magmatic rocks of the AMCAL-suite. In contrast to in situ anatexis by the anorthosite, it is a simple matter for gabbroic magmas ponded at the crust-mantle interface to melt lower crustal rocks. This is because repeated influxes of differentiating mafic magma can supply almost unlimited heat during differentiation towards more feldspathic compositions. Lower crustal anatectites are liable to be high in K_2O since: (1) orthoclase is a near-solidus phase in tonalitic and granodioritic rocks, and (2) anhydrous minima in the Qt-Ab-Or system move away from Qt with increasing P. These K-rich anatectites gather into batches and rise either as discrete plutons or as envelopes of acidic magmas about a core of feldspathic gabbro (leuconorite?) whose plagioclase cumulates will give rise to anorthosites. This is the mode of origin envisaged for the Adirondack AMCAL suite.

The emplacement of the AMCAL suite appears to have taken place under anorogenic conditions but was preceded by a regional metamorphism of garnet-sillimanite-K-feldspar grade and of unknown age. In the southern Adirondacks tonalitic gneiss dated by U-Pb zircon methods are, at least, 1320 Ma old and contain foliated xenoliths of metasediment. Along the St. Lawrence River foliated xenoliths are clearly evident in leucogranitic gneiss of the Rockport pluton dated at 1415±6 Ma by U-Pb zircon methods. Thus the pre-AMCAL suite metamorphism may be older than ~1415 Ma. The chemical signatures of these older meta-igneous rocks are calcalkaline and orogenic. The anorogenic AMCAL suite is evidently bracketed by compressional orogenies.

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COMPARISON OF ARCHEAN AND PHANEROZOIC GRANULITES: SOUTHERN INDIA AND NORTH AMERICAN APPALACHIANS. Harry Y. McSween, Jr. and Roger C. Kittleson, Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996, USA

Archean granulites at the southern end of the Dharwar craton of India and Phanerozoic granulites in the southern Appalachians of North America share an important characteristic: both show continuous transitions from amphibolite facies rocks to higher grade. This property is highly unusual for granulite terranes (1), which commonly are bounded by major shears or thrusts. These two terranes thus offer an ideal opportunity to compare petrogenetic models for deep crustal rocks formed in different time periods, which conventional wisdom suggests may have had different thermal profiles.

The salient features of the Archean (2600 m.y.) amphibolite-to-granulite transition in southern India have been recently summarized (1,2,3). The observed metamorphic progression reflects increasing temperature and pressure (600-600°C and 5-7 kbar in the amphibolite facies, 700-760°C and 6-8 kbar in the granulite facies). Granulite facies metamorphism appears to have been nearly isochemical. Migmatites are present, but are unrelated to the appearance of orthopyroxene. Amphibolite facies rocks contained hydrous fluids, but CO_2-rich fluids streaming through vertical shear zones in the granulite terrane appear to have promoted formation of orthopyroxene-bearing charnockites, overprinting other lithologic units.

Conditions for the Phanerozoic (450 m.y. = Taconic Orogeny) amphibolite-to-granulite transition in the southern Appalachians have been documented by (4,5). The following sequence of prograde reactions has been observed: (I) kyanite = sillimanite, (II) muscovite = sillimanite + K-feldspar, (III) partial melting of pelites, and (IV) hornblende = orthopyroxene + clinopyroxene + garnet. Reactions (II) and (III) appear to be nearly coincidental in the field, implying that incongruent melting of muscovite-bearing gneisses has occurred (muscovite + albite + quartz = K-feldspar + sillimanite + melt). Phase relations and mineral exchange equilibria indicate temperatures and pressures of 600-780°C and 5.5-6.8 kbar for amphibolite facies rocks and 680-780°C and 6.5-8.0 kbar for granulite facies rocks (summarized in Figure 1). Granulite facies rocks are defined by reaction (II); note that Indian granulites are defined by reaction (IV), due to differences in composition. Activity of water, aH_2O, estimated from paragonite and biotite dehydration reactions, decreases from 0.8 in amphibolites to 0.25 in granulites. There is no evidence of a fluid phase containing appreciable quantities of CO_2.

The mineral compositions of low-variance assemblages in mafic and intermediate rocks are almost identical for the two granulite facies assemblages. The P-T conditions for both the Indian and North American amphibolite-to-granulite facies transitions also appear to be remarkably similar, especially if comparisons are made on the basis of orthopyroxene-present and -absent assemblages. However, the fluid regimes were clearly different in these two terranes. The drop in aH_2O in the Appalachian granulite terrane appears to be related to scavenging of water by anatectic melts that were then vented to higher levels in the crust. This area did not experience flooding by CO_2-rich fluids of mantle or deep crustal origin, as in the case of Indian granulites. This diminished role for fluids derived from deep sources in the Appalachian granulites might suggest that degassing of the earth's interior over time could have changed the nature of granulite petrogenesis. Rare gas systematics do suggest that the mantle has undergone a slow and continuous outgassing to the present time, after an intense devolatilization within the first 500 m.y. of earth history (6). However, it is not at all clear that pervasive CO_2-rich fluids are a general characteristic of all Archean granulites.

The sets of P-T conditions for both Indian and North American terranes do not lie along a continental geotherm (at least for the present time), so mechanisms are needed for increasing regional geotherms. Crustal thickening has been advocated for both terrains (e.g. 1,8) to explain pressure data. The pressures at which these terranes equilibrated are similar to other granulites worldwide, which cluster at 7.5 ± 1 kbar (9). These consistent pressures suggest some recurrent tectonic process, such as overthrusting, is active in granulite petrogenesis of any age. Overthrusting would result in somewhat higher geothermal gradients, but other mechanisms may have been equally or more important. Volatile streaming has been suggested to have caused higher heat flow in the Indian terrane (7,10). In contrast, evidence for nearly isobaric cooling of granulites in the southern Appalachians led (4) to suggest that magmatic activity may have increased that regional geotherm. Similar retrograde cooling paths for granulites in some other areas may indicate that introduction of magmas into the crust is an important factor in determining the heat budget of such terranes.

In light of their different fluid regimes and possible mechanisms for heat flow augmentation, it seems surprising that these Archean and Phanerozoic granulite terranes were apparently metamorphosed under such similar conditions of pressure and temperature. This may be coincidental, although partial melting in both terrains may have acted in some way to buffer thermal conditions. Dehydration - melting reactions are endothermic and may be expected to constrain steady-state geotherms in regions of thickened crust (11). Comparison with other terrains containing continuous amphibolite-to-granulite facies transitions will be necessary before this problem can be addressed.

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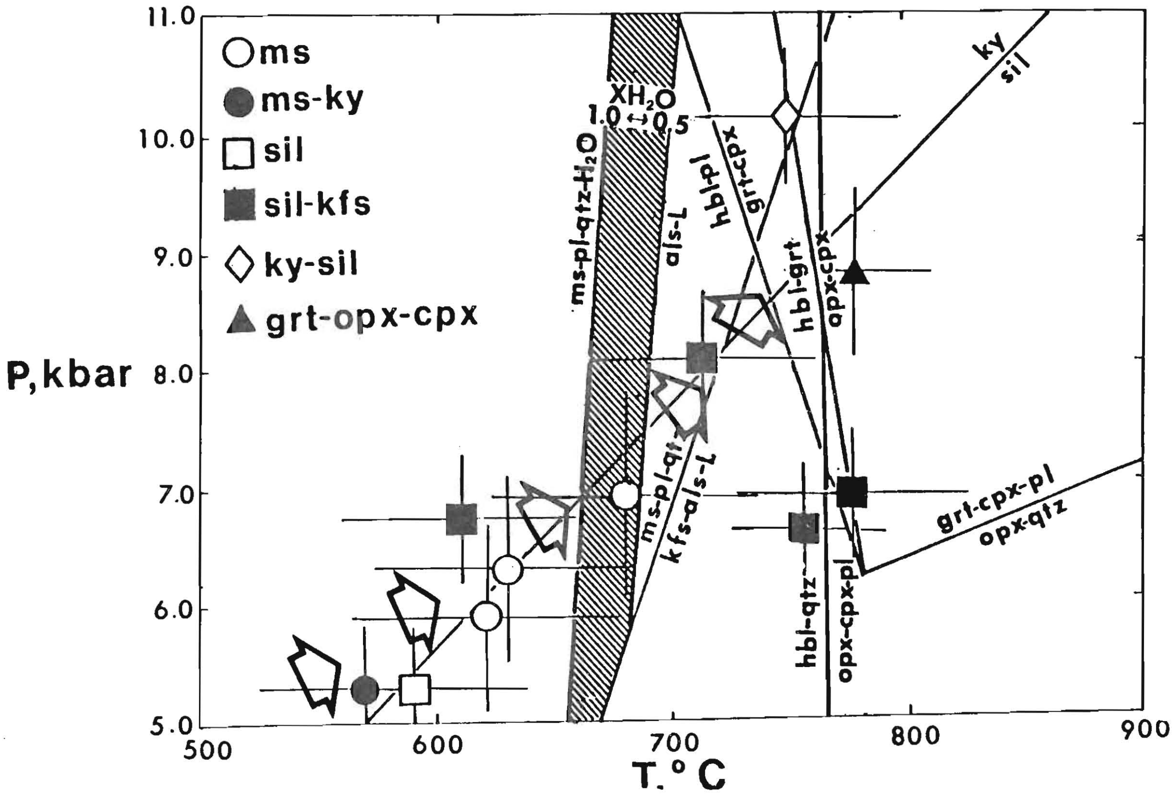

Figure 1. Pressure-temperature diagram showing locations of reactions in the amphibolite-to-granulite facies transition in the southern Appalachians, as well as P-T estimates from geothermometry and geobarometry. Garnet-biotite, garnet-clinopyroxene, and orthopyroxene-clinopyroxene geothermometers were employed; pressure calculations were based on garnet-plagioclase-aluminosilicate, garnet-plagioclase-muscovite, and garnet-orthopyroxene-clinopyroxene exchange equilibria. Compatibility of calculated P-T with phase relations is shown by mineral assemblages in the upper left corner. Arrows superimposed on the diagram delineate P-T calibrations along a traverse in southern India by (3).

P-T-t PATH FOR THE ARCHEAN PIKWITONEI GRANULITE DOMAIN AND CROSS LAKE SUBPROVINCE, MANITOBA, CANADA;

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Pressure-temperature-time (P-T-t) paths for metamorphic terranes coupled with thermal modelling should allow a quantitative reconstruction of the thermobarometric history of ancient mobile belts and may permit recognition of the style of tectonism. The accurate reconstruction of the evolution of a metamorphic terrane requires the determination of a quantitative pressure-temperature-time history, where actual pressures and temperatures can be combined with the absolute time they were reached in the rocks.

High precision ages for upper amphibolite to granulite grade gneisses were obtained by U-Pb dating of garnets. These ages, combined with pressures and temperatures obtained from different geobarometers and geothermometers, as well as mineral reactions observed in the gneisses, can be used to construct quantitative P-T-t paths (Fig. 1).

Based on textural evidence the following prograde reactions very likely have occurred in the rocks:

andalusite = sillimanite
staurolite + quartz = garnet + sillimanite + V
staurolite + quartz = cordierite + sillimanite + V
staurolite = garnet + spinel + sillimanite + V

and the following retrograde reactions:

hercynite + quartz = cordierite
garnet + sillimanite + quartz = cordierite
cordierite + hercynite = sillimanite + garnet

These retrograde reactions indicate that the terrane cooled isobarically or near-isobarically which is consistent with the garnet zoning in samples which contain the GRAIL assemblage (Mezger et al., 1986).

The prograde path at Cauchon Lake is defined by reactions at 2700-2687 Ma and then later at 2645-2637 Ma. The metamorphic event at 2700-2687 Ma locally led to the formation of partial melts and conditions above the stability of staurolite + quartz. The thermal event at 2645-2637 Ma caused extensive partial melting and probably the highest grade metamorphic conditions, as indicated by mineral assemblages containing the youngest generation of metamorphic garnets. All the high temperatures obtained from the two-feldspar thermometer and most of the pressures determined from the various mineral equilibria are interpreted to represent the "peak" conditions reached during this metamorphic event.

P-T-t PATH FOR THE ARCHEAN PIKWITONEI GRANULITE DOMAIN

K. Mezger et al.

The retrograde part of the P-T path corresponds to the cooling following the metamorphism at 2645-2637 Ma. At about 2600 Ma the terrane may have cooled to temperatures near the minimum melting point of granite. The introduction of fluids, together with the granitic melts at that time, locally caused extensive retrogression of the rocks to amphibolite grade and the resetting of the feldspar temperatures. The calculated cooling rate from 2637 Ma to 2600 Ma is ca. 3 °C/Ma.

Based on the anti-clockwise pressure-temperature path for the Pikwitonei granulite domain, the near-isobaric cooling path, the slow cooling rate and the multiple thermal events within about 150 Ma (Mezger et al., in prep.) we suggest that these granulites may have formed in a long-lived Andean-type continental margin rather than in a fold-and-thrust-belt.

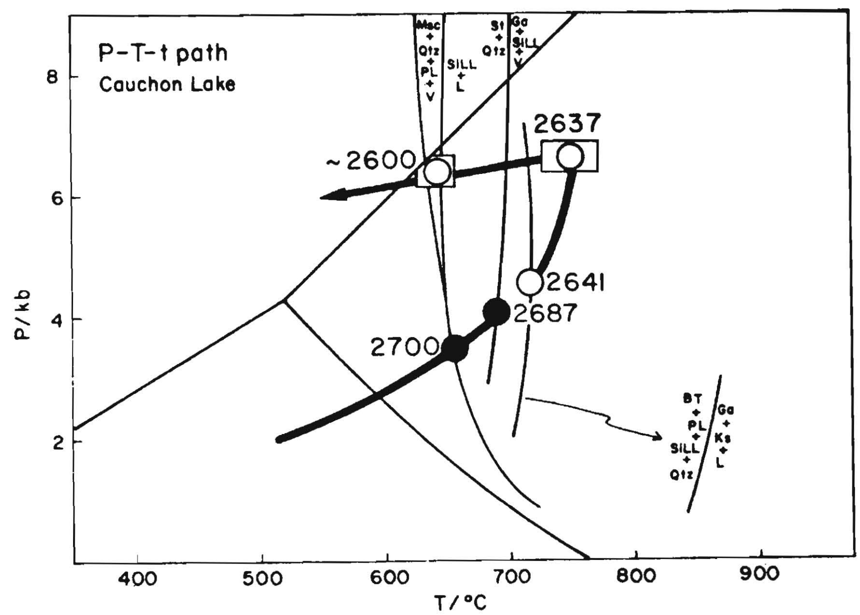

Fig. 1: P-T-t path for the Cauchon Lake are, Pikwitonei granulite domain - Cross Lake subprovince, Manitoba, Canada.

Mezger, K. et al., 1986; EOS 67, p. 407.

GEOPHYSICAL EVIDENCES FOR A THICK CRUST SOUTH OF PALGHAT-TIRUCHI GAP IN THE HIGH GRADE TERRAINS OF SOUTH INDIA; D.C.MISHRA National Geophysical Research Institute, Hyderabad 500 007, India.

The Bouguer anomaly map of India presents a prominent low (30-40 mgls) over the southern part of the continent (N.G.R.I., 1978) which coincides for a consederable part with the exposed charnockites (Fig.1a, Subrahmanyam and Verma 1986). North of this 'low' is an east-west, elongated 'high' of approximately 20 mgals almost perpendicular to the regional strke in the area. A fraction of these anomalies might be due to the shallow features but their large wavelengths suggest mainly deep seated sources. Significantly the gradient between these two anomalies coincide with the Palghat-Tiruchi line which is a prominent shear zone (Naqvi and Rogers 1987). The northern gradient of the Bouguer 'high' coincides with the Bhavani fault almost parallel to the Palghat-Tiruchi line which suggests its extension to a considerable depth. The occurrences of anorthosite bodies on either side of this gravity 'high' (Fig. 1a) also suggest a deep-seated origin for this anomaly. Topographically also, Palghat and Tiruchi depicts gaps in the western and eastern ghats respectively which might be manifestation of deep-seated structures.

A north-south profile across this 'high' and 'low' (Fig.1b) present a kind of Bouguer anomaly which is characteristic of the variations in the Moho signifying changes in the crustal thicknesses, 'low' corresponding to a thick crust and 'high' a thin one (Mishra et al. 1987). This inference has been supported also from deep seismic sounding studies in different tectonic regimes of the country including Peninsular Shield (Kaila et al 1979). In this regard the occurrence of this 'low' over the high grade terrain of S.India is very significant as it suggests a thick crust in this region. Such a situation under high grade terrains can arise only if the crustal accretion has taken place after the erosion of the upper crust or due to under-plating along a shear zone or old suture zone as described by Fountain and Salisbury (1981). The absence of oceanic sediments or volcanic and ultramafic rocks or their equivalents in this area does not favour the latter possibility of a suture zone. The Palghat-Tiruchi line may not be a true suture zone but can be considered as line of juxtaposition between two blocks as has been described by Thomas and Tanner (1975), inside 100 km of the Grenville Province.

The magnetic characteristics (Suryanarayana and Bhan 1985) around Palghat also changes significantly. The southern part depicting more intense magnetic anomalies than the northern part. MAGSAT has also shown an anomalous magnetic crust in this region (Mishra and Venkatrayudu 1985).The Palghat-Tiruchi line separating the 'low' and the 'high', therefore is very significant representing probably the junction of two blocks during the pre-cambrian period. These blocks might have over riden each other forming a thick crust towards the south from which even if the upper part is eroded away the remaining part is still thicker than a normal crust. The Bhavani fault towards north might have formed during this process sympathetic and parallel to this line. A closely-spaced profile recorded recently across these anomalies will be modelled and presented in the workshop to highlight the variations in the physical parameters and crustal thicknesses in the region.

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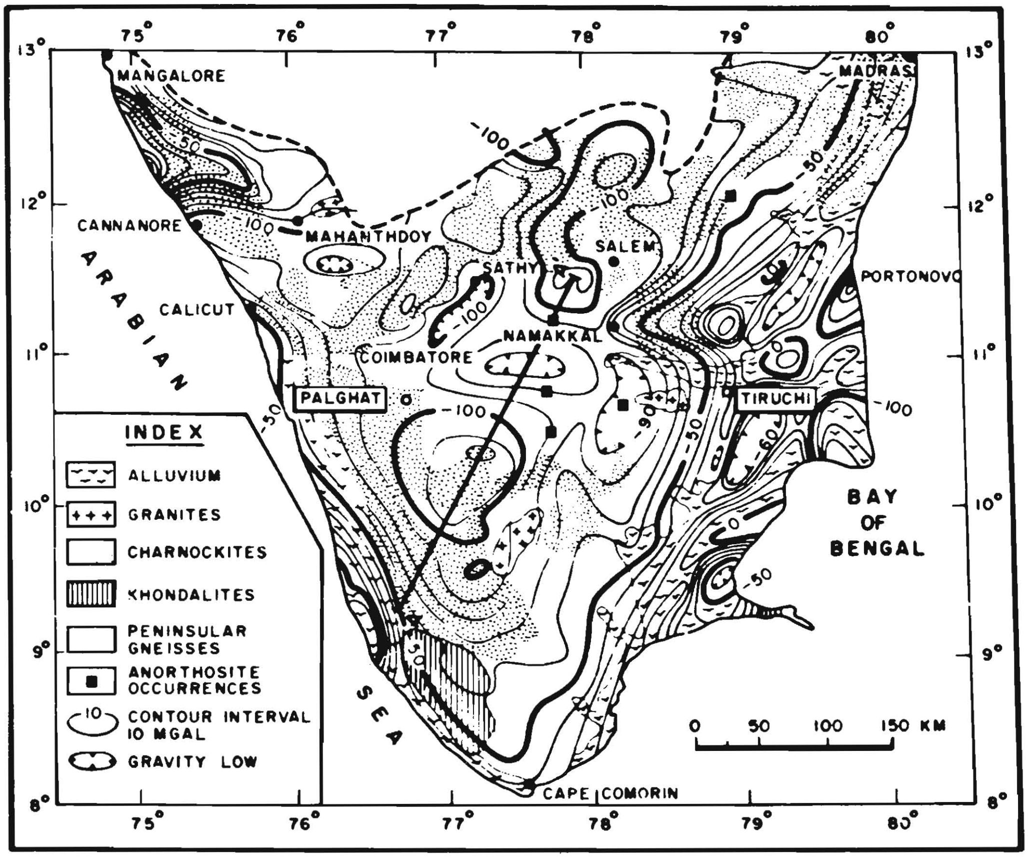

Fig.1a. BOUGUER ANOMALY MAP OF HIGH GRADE TERRAIN OF SOUTH INDIA

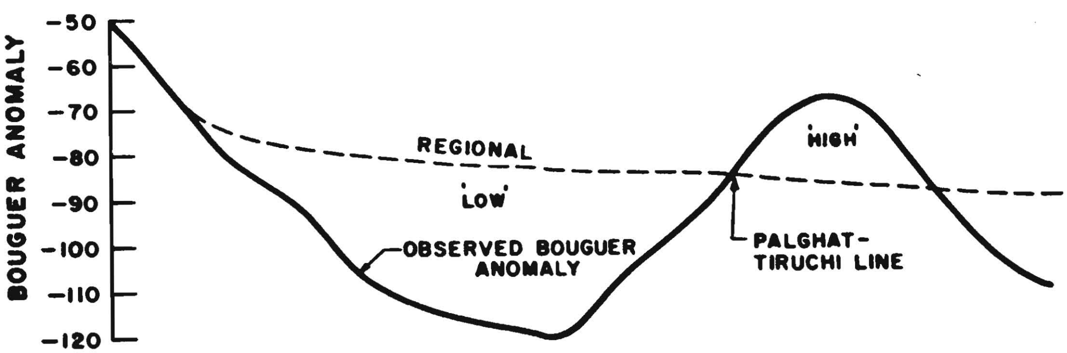

Fig. 1 b. BOUGUER ANOMALY PROFILE A A'

EARLY PRECAMBRIAN CRUSTAL EVOLUTION IN EASTERN INDIA: THE AGES OF THE SINGHBHUM GRANITE AND INCLUDED REMNANTS OF OLDER GNEISS.

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Extended Abstract.

The Singhbhum granite batholith complex covers an area in excess of 10,000 sq.km. on the border of the states of Bihar and Orissa in Eastern India (1). The oldest plutonic rock-units recognized within the complex are gneissic remnants, ranging in composition from biotite-tonalite to granodiorite. The gneissic remnants are quite numerous, and may be up to 1000 sq.km. in area. These tonalitic and granodioritic gneisses are assigned to the OMG (older metamorphic group), together with the metasediments and metabasics into which they were synkinematically intruded (1).

Basu et al (1) have reported a Sm-Nd whole-rock isochron date of 3775 +/- 89 Ma on OMG tonalitic and granodioritic gneiss samples from two separate areas within the Singhbhum granite batholith complex, near Champua and Onlajori. Their result is the oldest age yet claimed for rocks from the Indian sub-continent, and is amongst the oldest ages claimed for any terrestrial rock-unit. Basu et al (1) also reported an initial 143-Nd/144-Nd ratio of 0.50798 +/- 0.00007 for the OMG gneisses, corresponding to an initial ϵ(Nd) value of +3.3 +/- 0.9 units (2 sigma errors), unusually high in comparison with most other early Archaean cases (2), although an identical initial ϵ(Nd) value has been reported for 3.5 Ga amphibolites from Qianan County, eastern Hebei, China (3).

The claim of an early Archaean age for the OMG gneisses is clearly a very important development, and a high initial ϵ(Nd) value in early Archaean rocks has major implications bearing on the geochemical evolution of the crust-mantle system: a source for the OMG gneisses with a history of long-term LREE-depletion pre-3.8 Ga would be indicated, and also the existence of a long-lived complementary reservoir with LREE-enriched character. [See ref.(3) for a discussion of the implications of high positive ϵ(Nd) values in early Archaean rock-units.] It is therefore important to seek evidence to confirm the results and interpretations put forward by Basu et al (1).

First, a review of the published Sm-Nd data on the OMG gneiss samples used to construct the 3775 Ma isochron (1) can be made by examining the Nd isotopic evolution of individual samples in a diagram of ϵ(Nd) versus Time. Seven of the nine OMG samples, those with the lowest Sm/Nd ratios, have Nd isotopic evolution lines which intersect DePaolo's (4) empirical depleted mantle [DM] growth curve over a very small age range from 3.52 Ga to 3.45 Ga [i.e. they have T-DM model ages (4) of 3.52 to 3.45 Ga.] The two other samples are less enriched in LREE, and they have lower T-DM model ages of 3.27

and 3.30 Ga. This difference suggests either that these two samples may be younger phases, entirely unrelated to the main group, or perhaps more likely, that they are related rocks, but with later added component(s). It could be significant that both the Onlajari and Champua tonalitic gneisses have been invaded by abundant perthite-muscovite pegmatites (1). On either of these interpretations, there are grounds for concern that the 3775 Ma line might be an artefact resulting from combining materials of different ages for an isochron determination. The Sm-Nd model ages [T-DM] strongly suggest that none of the analysed OMG gneisses is actually as old as 3775 Ma.

Three additional samples of OMG gneisses from other localities within the Singhbhum granite batholith complex [kindly made available to us by S.N.Sarkar and A.K.Saha] give T-DM model ages of 3.41, 3.39, and 3.35 Ga, slightly younger than the model ages discussed above. Two samples of the Singhbhum granite [also supplied by S.N.Sarkar & A.K.Saha] give essentially identical T-DM model ages of 3.36 and 3.40 Ga. From this we conclude that the crustal residence ages of OMG gneisses and the main intrusive phases of the Singhbhum granite are very similar.

The disparity between the 3775 Ma Sm-Nd OMG gneiss isochron result and the ca. 3200 Ma Rb-Sr whole-rock isochron result reported by Sarkar et al (5) for the same suite of samples also merits attention. Basu et al. (1) offered two possible explanations: in their preferred model, formation of the OMG occurred at ca. 3800 Ma, followed by metamorphic resetting of Rb-Sr whole-rock systems at ca. 3200 Ma. However, if the T-DM model ages above are accepted as a reliable constraint on the crustal residence age of the OMG gneisses, the discrepancy between Sm-Nd and Rb-Sr age estimates is greatly diminished. The low initial 87-Sr/86-Sr ratio of ca. 0.7018 for the OMG gneisses in the Champua area (1,5) can also be considered as evidence against long crustal residence prior to 3200 Ma for the precursors of these rocks.

In a study of OMG gneisses provided by S.N.Sarkar & A.K.Saha, we have also obtained a Rb-Sr whole-rock isochron age of 3280 +/- 130 Ma, together with an initial 87-Sr/86-Sr ratio of 0.701 +/- 0.001 [2 sigma errors; 7-point isochron with MSWD 3.7] (Oxford unpublished data; 6). A Pb/Pb whole-rock isochron for the OMG gneisses gives an age of 3378 +/- 98 Ma, and a model μ1 value of 8.01 [7-point isochron with MSWD 1.1] (6). Thus, comparison of Sm-Nd model ages [T-DM], and Rb-Sr and Pb/Pb whole-rock isochron ages for the OMG gneisses analysed at Oxford shows good agreement, within the limits of analytical error. Furthermore, the low initial 87-Sr/86-Sr ratio of 0.701, the model μ1 value [source 238-U/204-Pb ratio] of 8.01 for these rocks, and their Nd isotopic compositions at ca. 3.35 - 3.4 Ga, typical of a depleted mantle source at that time, all strongly suggest that the OMG gneisses represent continental crust newly generated at ca. 3.35 - 3.4 Ga.

For the Singhbhum granite, a Pb/Pb isochron yields an age of 3292 +/- 51 Ma and a model μ1 value of 7.97 [8-point isochron with MSWD 2.5] (6). The T-DM model ages [3.36 & 3.40 Ga] for Singhbhum granite samples imply that their protoliths were extracted from the mantle at the same time as OMG gneisses. The Pb/Pb isochron ages of Singhbhum granite and OMG gneisses are also closely similar. Thus the chronology of events in the development of the Singhbhum granite batholith complex is not yet adequately resolved by isotopic dating. At this stage it must depend principally on critical field observations of structural and intrusive relationships between the constituent rock bodies of the complex. What is clear from the isotopic evidence is that the interval of time separating the formation of the earliest recognized plutonic phases of the Singhbhum granite batholith from the main phases of granite intrusion was not great: Sm-Nd model ages indicate up to ca. 150 Ma, not ca. 600 Ma as previously suggested (1).

The Singhbhum granite and its included gneissic remnants do constitute some of the oldest continental crust yet recognized within India. [Gneisses of similar age are known from the Gorur - Hassan area in the Karnataka Craton of South India. (7) & R.D.Beckinsale, pers. comm.] However, the claim of an age as great as 3775 Ma must be regarded with very serious reservations. Furthermore, the high initial ϵ(Nd) value of +3.3 from the OMG Sm-Nd study (1) should not be used in support of very early separation of LREE-enriched [continental?] crust from the upper mantle, or as evidence of a complementary early LREE-depletion of the mantle. The initial ϵ(Nd) value from the OMG "isochron" is most probably, like the high apparent age of 3775 Ma, an artefact resulting from the inclusion in the isochron set of two samples containing younger component(s) less enriched in LREE than the main group of OMG gneisses.

We should like to express our thanks to S.N.Sarkar and A.K.Saha for providing the samples of the OMG gneises and the Singhbhum granite for this study, and we also thank Roy Goodwin for skilled technical assistance with Rb-Sr and Pb isotopic analyses, and John Arden and Martin Whitehouse for help with Sm-Nd analyses.

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HEAT TRANSFER BY FLUIDS IN GRANULITE METAMORPHISM;

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Granulite metamorphism represents the extremes of crustal conditions short of melting. These extreme conditions place important constraints upon models that can be used to explain the generation of granulites which we find exposed at the surface. In this short contribution we examine these constraints and discuss the role of fluids in granulite metamorphism, with special reference to the granulites of southern India.

Requirements of Granulite Metamorphism

Granulite metamorphism requires temperatures in excess of 700°C, and pressures are commonly recorded in exposed granulites indicating burial depths of 15 to 30 km. Nearly all examples of exposed granulite rocks contain at least some component of supracrustal rocks, including sediments, volcanics, or other rock units which formed at or near the Earth's surface (1). These granulites are now exposed on the surface of normal thickness crust (35 to 40 km). Thus, three components are required in any mechanism proposed to explain granulite metamorphism:

1) Transport of supracrustal rocks to 15-30 km;
2) Heating to 700°C or higher; and
3) Re-exposure at the surface of normal thickness crust.

Models for Regional Metamorphism

Models of regional metamorphism can be divided into two basic groups for the purpose of understanding granulite metamorphism: Monogenetic and Polygenetic models. In monogenetic models the transport of supracrustals to 15 to 30 km and the re-exposure at the surface are assumed to result from a single tectonic event. The commonly invoked mechanism invoked in this context is continental underthrusting and crustal thickening through which the supracrustals are transported to depth by underthrusting, and re-exposed by isostatic uplift and erosion of the thickened crust. The constraint that the exposed granulites are always underlain by 35 to 40 km of crust is inherent in this mechanism. In polygenetic models, transport to depth and re-exposure are assumed to result from different tectonic events. The supracrustals can be transported to depth either by underthrusting as in the monogenetic models, or by deep burial associated with multiple extensional crustal thinning events (isostatic considerations suggest that single events are unlikely to produce sedimentary basins much greater than 10 km, even under the most favorable assumptions). Re-exposure then results from an independent tectonic event, either a compressional event in which the granulites are overthrust onto a normal thickness crust, or through tectonic unroofing during extension, although the normal thickness crust constraint requires that this extension takes place in an overthickened crust.

We have so far ignored the second necessary component of granulite formation, the heating to 700°C or more. This component places important constraints upon heat transfer associated with granulite metamorphism. In all monogenetic models of granulite formation, and the polygenetic models which invoke tectonic unroofing during extension, a minimum of 35 to 40 km of crust beneath the granulites is required at the time of their heating and formation. As the granulite mineralogies commonly indicate burial depths of 15 to 30 km, they would have been formed roughly quarter to half-way down an overthickened crustal section. Taking a very simplistic view that the geothermal gradient is uniform throughout the crust, the Moho temperature would be expected to be two to four times the temperature at the depth of granulite formation: i.e., 700°C at the granulite formation depth implies Moho temperatures of 1400 to 2800°C. It is obviously over-simplistic to assume a uniform geothermal gradient throughout the crust, but as shown by Ashwal and others (1), if steady-state conductive conditions are assumed, it is impossible to devise a geotherm based upon realistic heat production values and thermal conductivities that decreases sufficiently with depth to allow temperatures of 700^{o}C or more in the mid to upper crust without super-solidus temperatures in the lower crust. This constraint is removed if the granulites are formed in the lower crust and erosionally exposed following subsequent thrusting over crust of normal thickness. Alternatively, the steady-state conductive geotherm may be modified by the effects of convection in the crust.

Heat can be convected in the crust by the movement of fluids through the crust or by movement of the crust itself relative to the surface. We consider the latter form of convection first. General upward movement of the crust in isostatic response to erosion or tectonic unroofing has the effect of making the geotherm convex upward and raising temperature in the upper crust. Numerous examples of this effect are given by England and Thompson (2) for a variety of initial assumptions for monogenetic regional metamorphism models. However, although the required geotherm can be modelled by this mechanism, examination of pressure-temperature-time (PTt) paths for rocks initially buried in the mid to upper crust, shows that these rocks cool as a result of uplift and only pass through the granulite formation temperature field for models in which massive melting (super-solidus temperatures) is predicted in the lower crust. Maximum temperatures are attained at any specified horizon when the erosion rate is a minimum after crustal thickening, i.e., under steady-state conditions. Significantly increased temperatures at any specified horizon can only be generated by the upward convection of fluids through the crust, either magma or volatiles.

Models of magmatic convection of heat into the crust and the resulting metamorphism have been presented by Wells (3). These models show that the sustained addition of magma to the crust profoundly influences the geotherm, primarily at levels in the crust below the depth of magmatic accretion to the crust. Thus, the most efficient mode in which to produce granulites by this mechanism would be through intrusions into the upper crust, above the level at which the granulites are formed. Unfortunately these intrusions would be eroded before the granulites could be exposed, but some evidence of the passage of magmas through the granulites may be expected to remain. If no evidence exists for magmatism associated with metamorphism, heat transfer by volatiles may be a viable mechanism.

Advection of heat and matter by fluids during metamorphism has recently been studied by Bickle and McKenzie (4) for the case in which the rock is modelled as a porous medium, and heat transport is laterally homogeneous. At depth, however, it is likely that fluids flow through discrete fractures, and we have started to investigate metamorphism associated with fracture-controlled fluid-flow. Bodvarsson (5) has presented solutions for heating associated with water flowing through fractures for a limited set of flow conditions and single planar-fracture geometries. We use these solutions to estimate the effect of steady constant-temperature fluid-flow through a system of vertical planar-fractures in the crust. If vertical heat transfer in the rock medium is neglected, crustal temperatures are dominated by the temperature of the ascending fluid, which is of the form:

$$T = T_o \operatorname{erfc}\{A(d-z)\}$$

where T_o is the temperature of the base of the crust and the temperature at which the fluid enters the fracture, erfc{ } is the complementary error function, d is the crustal thickness, z is depth, and A is a constant, defined by the flow rate, the ratio of fluid to rock thermal properties, and the time since the flow started. Preliminary calculations suggest that, for water, very modest flow rates (of the order of 0.1 g/s per m of horizontal fracture length) can significantly modify the geotherm, and that flows sustained over time periods of 1 ka to 1 Ma, depending upon fracture spacing, can produce temperatures compatible with granulite metamorphism in the mid to upper crust without requiring melting in the lower crust. More complete numerical studies by Hoisch (6) support these results and conclusion.

Granulites of Southern India

Summaries of the geology of the Southern Indian Shield (7, 8) suggest that granulite metamorphism in the southern portion of this shield was associated with a late Archean and/or early Proterozoic mobile belt in which the crust was thickened by compressional deformation.

There is abundant evidence for CO_2-K metasomatism throughout the shield, and we tentatively suggest that fluid-flow associated with this metasomatism was the primary agent of heat transport for the granulite metamorphism. Definition of a plate-tectonic regime associated with this deformation/metamorphism even is controversial, but it seems likely that compression and fluids for metasomatism/metamorphism were associated with early Proterozoic subduction.

Acknowledgements

This study has benefitted greatly from discussions with Tom Hoisch, and we gratefully acknowledge access to the results of his numerical models studies prior to publication with which we have checked the approximations used in our analytical solutions.

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THE PETROGENETIC SIGNIFICANCE OF PLAGIOCLASE MEGACRYSTS IN ARCHEAN ROCKS.

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Introduction: Plagioclase-megacryst bearing rocks occur in all Archean terrains as basalts, as hypabyssal units, including sills which appear to have transitions to extrusive rocks, as large scale anorthositic intrusives, and as dikes forming post-tectonic swarms emplaced over very large areas [1]. All of these occurrences are characterized by the presence of equant plagioclase megacrysts of homogeneous An content, typically greater than An80. The volcanic and hypabyssal units occur in greenstone belts and are associated generally with supracrustals. Some anorthosite complexes are associated with volcanics and supracrustals. Dikes with megacrysts form large swarms cross-cutting both greenstone and granite-gneiss terrains. Geochemical data suggest that the parent melt and the processes which generate the megacrysts and their host rocks are the same in all tectonic settings.

Parent melt of anorthosites: Archean anorthosite complexes are cumulates composed of plagioclase megacrysts in a mafic matrix and range in mode from anorthositic to gabbroic. The Bad Vermilion Lake complex of Ontario [2] is a representative of such complexes. Parent compositions corresponding to large scale anorthositic cumulates are not directly observable, however, estimates can be made through mineral-melt relationships because the megacrysts represent equilibrium and isothermal crystallization conditions. Individual plagioclase megacrysts from two anorthositic intrusives, but particularly from the Bad Vermilion Lake intrusive, were analyzed in detail via a multiple aliquot technique [3]. The multiple aliquot technique helps to sort out the effects of alteration allowing better estimates to be made of indigenous trace element abundances. Results show that the megacrysts crystallized in equilibrium with a parent liquid depleted in light rare earths and with abundances comparable to those commomly observed in basalts (if the plagioclase/melt partition coefficients of McKay [4] are employed). The possibility that light rare earth depleted basalts may be parental liquids for Archean anothosite complexes is further suggested by the presence of plagioclase megacrysts in basalt flows and basaltic sills and dikes.

The major element compositions of megcryst-bearing volcanic rocks which are likely to represent liquids fall in a cluster corresponding to tholeiites. The average composition of Archean megacryst-bearing tholeiites from the Canadian Shield is shown in table 1. This composition is olivine normative. The Mg* number ($Mg^*=MgO/MgO+Fe+0.9(2Fe_2O_3+FeO)$ where $FeO/Fe_2O_3=8.1$) is 0.54 indicating a relatively evolved composition. In all of the megacryst-bearing basalts, iron contents are relatively high (11 to 13% FeO_t) and Na_2O contents cluster around 2%. In relatively unaltered flows, the An content of lathy, zoned matrix plagioclase is lower than that of the megacrysts but megacryst rims, typically a few hundred microns thick, reflect the compositional ranges of the matrix plagioclase.

Rare earth abundances in megacryst-bearing volcanics and associated sills are invariably light rare earth depleted and range from approximately 10 to 15 times chondrites. These are the characteristics predicted by the rare earth data from the anorthosite cumulates. Rare earth contents of megacrysts in the flows (determined for plagioclase separates) allow equilibrium between megacrysts and matrix but there is some variation in the heavy rare earths, probably as a result of alteration, resulting in some ambiguity.

Parent melts of dike swarms: Megacryst bearing dikes from the Matachewan swarm of Ontario have been analyzed using multiple aliquot techniques. Chilled margins of the dikes are tholeiitic but distinctive from the volcanics. An average composition, representing 36 dikes from the swarm is shown in table 1. This composition is marginally quartz normative, however the dikes vary from olivine to quartz normative. The Mg* number of the averaged composition is 0.46, and dike rocks tend to have a higher alkali component than megacryst-bearing volcanics. In relatively unaltered rocks, plagioclase megacrysts show wave like fluctuations in An content of a few (+/-2) An units, as is also observed in cumulates of the Bad Vermilion Lake type. Groundmass plagioclase laths are more sodic and progressively zoned. Rims of megacrysts (5 to 6% of the total volume) reflect groundmass plagioclase compositions.

Rare earth abundances in these dike rocks are somewhat higher than in the basalts. The dikes can be divided into three groups, 1.) depleted, 2.) enriched, and 3.) highly enriched, based on the rare earth abundances. All three groups have similar major element abundances. Both depleted and enriched dikes occur in greenstone terrains, but only enriched dikes occur in granite-gneiss terrains. Plagioclase megacryst/matrix rare earth abundance ratios equal the partition coefficients determined experimentally by McKay [4] for plagioclase/lunar basalt compositions crystallizing over approximately the same temperature range. This agreement, also observed in the flows and sills, indicates equilibrium between megacrysts and matrix, strongly suggesting that the matrix represents the parent liquid of the megacrysts.

Given the above observations, it appears that the parent liquid from which plagioclase megacrysts in intrusives, sills, flows and dikes are generated is represented by megacryst-bearing sills and flows and at least some dikes. This hypothesis has been tested experimentally. Powders prepared from megacryst-bearing sills from the Bird River area of Manitoba were crystallized at one atm under FMQ conditions. The results show that plagioclase megacryst-bearing basalts could produce the megacrysts they contain and that plagioclase of the appropriate An content is on the liquidus for approximately 25^0 C before cpx appears. For an An content of 80, the plagioclase/mafic ratio is 7/3 approximately, and about 10% of the melt is transformed to plagioclase of megacryst composition. Preliminary experiments at 10 kbs show that this composition crystallizes augite before plagioclase and that the first plagioclase to appear is more sodic than An80. The experimental data support the proposition that tholeiites of the type shown in table 1 could represent a parent liquid for various plagioclase megacryst-bearing rocks including Archean anorthositic intrusives. Compositions cluster around the one atm co-tectic on the Pl-Di-Ol pseudoternary and the experimental data limit the process to moderate to low pressures. If this hypothesis is correct then limits can be placed upon the crystallization conditions.

<u>Crystallization Conditions</u>: The homogeneity typical of Archean plagioclase megacrysts requires growth in a nearly isothermal environment. Crystallization takes place in mid to upper crustal-level chambers. Individual megacrysts from large scale intrusives (e.g. the Bad Vermilion lake mass) and from Matachewan dikes have smooth oscillations in An content from their cores to within a few hundred microns of their much more sodic rims. These oscillations suggest replenishment of the parent liquid during crystallization of the megacrysts. In addition, rare earth abundances and slopes in dike rocks vary greatly for approximately constant major element composition. The rare earths are de-coupled from the major elements. This characteristic, together with the indications of rejuvenation of the parent liquid shown by the megacryst An content, is typical of magma replenishment during crystallization and the establishment of perched major element compositions in an otherwise evolving liquid. Most, but not all, of the incompatible element de-coupling and enrichment observed in the dike rocks can be accounted for through replenishment processes. However replenishment processes cannot account for the range in slope and abundances observed between depleted (MORB-like) dikes and those with highly enriched patterns (La/Sm > 1.8). In these cases, source differences, and/or variation in amounts of partial melting of a single source may be required. (Assimilation partially resolves differences but the amount of assimilated material required is large).

Anorthosite complexes such as at Bad Vermilion Lake place further limits on crystallization conditions. The Bad Vermilion Lake complex is layered on a large scale [5]. Individual units, hundreds of meters thick, vary in their mode and in the size frequency distribution of their megacrysts. Some units have distributions indicating sorting of megacrysts during cumulate formation. Contacts between units which differ in degree of sorting are observable. Flow and sorting during cumulate formation appear to have been important. The density of the liquid is equal to that of the plagioclase at the temperature of crystallization (about 1200^0 C.), consequently the megacrysts are neutrally buoyant in the liquid from which they crystallize. In addition, the large size of the megacrysts suggests few and scattered nuclei during crystallization and little or no supercooling. The Bad Vermilion Lake intrusive and other large scale cumulates suggest the presence of large periodically replenished magma chambers, through which very large amounts of liquid were moved to become volcanics. The cumulates represent 10 to 15% of the parent liquid volume.

Summary: Archean plagioclase megacryst-bearing rocks form in mid to upper crustal level magma chambers which are repeatedly replenished. Crystallization is nearly isothermal and is an eqilibrium process. Cumulates are formed, probably in marginal zones of the chambers, and liquids bearing megacrysts are extracted to appear as volcanics. Flows and some intrusives occur in arc-like environments in greenstone belts. Dikes represent large volumes of melt. The areal extent of dike swarms like the Matachewan swarm suggests multiple sources of like composition. Primitive liquid(s) evolve to Fe-rich tholeiite compositions (and acquire contaminants) then move to mid- to upper crustal levels where megacrysts are formed. Complex sequences of ponding and melt migration are probable and involve large amounts of liquid.

TABLE 1: AVERAGED COMPOSITIONS OF MEGACRYST-BEARING FLOWS AND DIKES

	SiO_2	Al_2O_3	TiO_2	FeO	MgO	CaO	Na_2O	K_2O	LOI
Aver. Flow	48.8	15.4	1.02	11.6	6.9	11.7	1.97	0.18	1.97
Aver. Dike	50.7	13.6	1.34	13.5	5.8	9.4	2.45	0.68	1.45

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POST-METAMORPHIC FLUID INFILTRATION INTO GRANULITES FROM THE ADIRONDACK MTS., USA; J. Morrison and J.W. Valley, University of Wisconsin- Madison.

The Adirondack Mountains of New York (USA) are a classic granulite facies metamorphic terrane and as such have been the focus of many studies concerning the role of fluids in the development of granulites. Most studies to date in both the Adirondack and the S. India granulites have addressed the nature of processes that operate during metamorphism as well as pre-metamorphic has been conducted on post-metamorphic retrogressive processes, which recent studies have shown to have important implications for granulite petrogenesis as well as geochronology and geophysical properties of the crust.

During the Grenville Orogeny at $\sim$ 1.1 Gyr, metamorphic grade in the Adirondacks varied from amphibolite facies in the NW Lowlands (6.5-7.0 Kb, 650-700 °C) to the granulite facies (7.5-8.0 Kb, 750-800 °C) in the Highlands[1]. The Marcy anorthosite massif, a major lithologic unit in the granulite facies of the Adirondacks, is a large ($\sim$12,000 km^3), homogeneous batholith composed predominantly of plagioclase ($\sim$ An_{45}) with lesser amounts of pyroxene, garnet and Fe-Ti oxides. Approximately 90% of 150 anorthosite samples contain post peak-metamorphic alteration assemblages of calcite, chlorite, sericite, quartz, pyrite, pyrrhotite, epidote, scapolite and prehnite. The percentage of alteration is variable and ranges from a trace to 10 volume%.

Two distinct textures characterize the alteration assemblages: veins and disseminated phases. The veins are discrete and cross-cut plagioclase megacrysts, garnet, orthopyroxene, clinopyroxene and Fe-Ti oxide. The larger veins (>0.5 mm wide) are often symmetrically zoned with calcite cores surrounded by chlorite then sericite. Smaller veins (<0.5mm wide) are generally composed of either chlorite or calcite. In addition to the veins, alteration minerals occur disseminated throughout both plagioclase and the mafic minerals, and as 'clots' within the interstitial mafics. These assemblages, which document post metamorphic fluid infiltration, are readily visible by normal petrographic techniques. However, transmitted light microscopy alone does not reveal all of the manifestations of the retrograde fluid infiltration. Cathodoluminescence of apparently unaltered samples reveals anastomosing veins of calcite (<<0.05 mm wide) that lie along cleavage or partings in mineral grains, along cross-cutting fractures and along grain boundaries. These calcite veins indicate that the retrograde fluid infiltration was more extensive than indicated by transmitted light petrography alone[2].

This widespread retrograde fluid infiltration has important implications for studies of granulite genesis. Substantial controversy surrounds the relative importance of the four mechanisms that have been proposed to account for the low water activities (aH_2O) that characterize granulites: 1) partial melting which would cause a preferential partitioning of water into the melt phase, 2) passage of dry magmas through the crust, 3) pervasive infiltration of deep-seated CO_2 which would dilute the metamorphic fluid and reduce the aH_2O, or 4) metamorphism of already dry rocks. In particular, controversy surrounds the importance of CO_2-flooding[3,4,5]. The presence of high density CO_2-rich fluid inclusions in granulites is often interpreted as evidence for infiltration of massive amounts of CO_2 during metamorphism. Lamb et al.[6] have shown that some high density CO_2-rich inclusions in samples from the Adirondacks must have been trapped after the peak of metamorphism, yet the origin and nature of the retrograde fluids has been poorly understood. In some samples textural relations between high density CO_2-rich inclusions and secondary minerals indicate that entrapment of the inclusions is concurrent with mineralogic alteration. For example, veins of sericite and chlorite crosscut clinopyroxene and where they intersect quartz, trails of high density CO_2-rich fluid inclusions are developed. We interpret this texture to indicate that the fluid inclusions have trapped the same fluids that caused the mineralogic alteration. This textural association of high density CO_2-rich fluid inclusions and retrograde minerals is particularly important in light of the cathodoluminescence results which indicate that many apparently pristine samples have been infiltrated by retrograde CO_2-H_2O fluids.

We have analyzed the carbon and oxygen isotope composition of calcite in 30 altered anorthosite samples in order to evaluate the provenance of the retrograde fluids. Values of $\delta^{18}O$ (SMOW) range from 11.1 to 15.0 ‰ and values of $\delta^{13}C$ (PDB) range from 0.2 to -4.0 ‰. Coexisting calcite and the host plagioclase have been analyzed for $\delta^{18}O$ to evaluate whether the isotopic composition of the calcite is controlled by the host rock or the hydrothermal fluid. Values of Δ_{cc-pl} range from 0.9 to 5.8 which we interpret to indicate that the oxygen isotope composition of the calcite was controlled primarily by the hydrothermal fluids. Mixed H_2O-CO_2 fluid inclusions provide minimum temperatures for the alteration of $\sim$350 °C. The calcite values are intermediate between those of igneous rocks and marbles, which suggests that the hydrothermal fluids exchanged with both meta-igneous and supracrustal lithologies.

The precises timing of the hydrothermal vein formation is not yet known. If the fluid infiltration occurred during uplift from granulite facies pressures and temperatures (maximum depths = 24-26 km at $\sim$ 1.1 Ga), then the alteration assemblages and associated fluid inclusions will provide important constraints on pressure-temperature-time paths of uplift as well as the nature of mid crustal fluid movements. Alternatively, if the fluid infiltration occurred during the Phanerozoic then these veins provide important information about large scale fluid movements associated with the Taconian or Acadian orogenies as suggested by Oliver[7].

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STRUCTURAL EVOLUTION OF THE KOLAR SCHIST BELT, SOUTH INDIA;
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The small-scale deformational structures in the banded ferruginous quartzite near the western margin of the Kolar schist belt indicate four generations of folding episodes (F_1-F_4). The F_1 and F_2 folds are very tight to isoclinal with long, drawn-out limbs and sharp hinges of insignificant areal extent. The F_1 folds affect only the well preserved bedding planes whereas the F_2 folds affect F_1 axial planes and related foliation as well as bedding planes. However, in a major part of the area the F_1 axial plane foliation is not well developed in the scale of outcrop though it is clearly seen under microscope. Consequently, the F_1 and F_2 folds are largely indistinguishable from each other in the field unless both the sets are present in the same exposure and, therefore, they have been grouped together as early folds.

The F_1 and F_2 folds are nearly coaxial resulting in a type 3 interference pattern. Their axial planes are also effectively parallel except at the hinges of F_2 folds where they are at high angles. The north-northeasterly striking early axial planes usually dip very steeply whereas the axes show wide variation in plunge from subhorizontal to vertical with more or less constant NNE-SSW trend (Fig. 1a). The overprinting relation is such that both the F_1 and F_2 folds are plane noncylindrical except at the hinges of F_2 folds where F_1 folds are nonplane noncylindrical. Disharmony at the fold hinges, combination of class 1C and class 3 types of folds in alternate competent and incompetent layers in a multilayered sequence, thicker bands showing folds of larger wavelength, and parasitic folds at the hinges of folds of larger order indicate that the early folds were initiated by buckling (layer parallel compression). However, high amplitude to wavelength ratio and boudinage, pinch-and-swell structures and rod-like structures lying parallel to the axial planes point to importance of post-buckle flattening in shaping the folds.

The folds of the third generation (F_3) are a set of open and recumbent or gently plunging reclined folds with axial planes dipping gently towards ESE or WNW and axes trending in NNE-SSW direction. These folds have developed due to gravitational collapse of the subvertical foliation planes under their own weight. The F_4 folds are of the nature of warps sporadically becoming tight with vertical axial planes striking from NE through E to SE (Fig. 1a). The axes of F_4 folds plunge down the dips of local foliation planes which are usually steep. These folds have developed in response to a longitudinal shortening at the waning phase of folding episodes. The F_3 and F_4 folds affect each other and at places F_3 folds are dominant. Elsewhere F_4 folds are stronger indicating that these two fold systems are broadly synchronous. However, the only effect of these two sets is seen in minor modification in orientation of early structures and they are unimportant in large scale.

Mesoscopic ductile shear zones, subparallel or at low angle to foliation planes, are uncommonly well preserved in the ferruginous quartzite. Within the shear zones foliation planes, early axial planes and layerings are sygmoidally curved from which sense of movement can be easily determined. Both sinistral and dextral shear zones have been noted. A new set of steeply plunging and asymmetrical S- and Z-shaped folds with axial planes at low angle to the early axial planes have developed in shear zones. Subhorizontal striations and mineral lineations on shear surfaces are deformed by later folds indicating that the shearing movement is pre-F_3 in age. Steeply dipping shear zones, which are often conjugate, are also present in the Peninsular gneiss on either sides of the schist belt. The modal strike direction of sinistral shear zones is N335^{o} and that of the dextral shear zones is N35^{o} (Fig. 1b). These two orientations form a conjugate pair, the bisectors of which give horizontal maximum and minimum compressions in N95^{o} and N5^{o} directions respectively with the intermediate compression direction being vertical (Fig. 1b). As the shear zones on either sides of the schist belt give similar orientation of compression directions separately, it may be concluded that the same movement was responsible for the development of shear zones in the ferruginous quartzite also. The early folds became noncylindrical largely due to this shearing movement.

The deceptively simple map pattern of this schist belt with N-S linear disposition of major lithological boundaries, therefore, conceals two phases of coaxial isoclinal folding in large scale and a shearing movement subparallel to the axial planes.

It is suggested that a subhorizontal and nearly E-W simple shear acting on subhorizontal bedding planes resulted in isoclinal and recumbent/gently plunging reclined folds with NNE axial trend. The F_2 folds with NNE trending axes, which coaxially refold F_1 folds, formed in response to a pure shear in the same direction. Continued compression tightened the F_2 folds into isoclines and when they could not be flattened any further shearing movement was initiated. As the nearly E-W compression direction was at a high angle to the steeply dipping foliation planes the shear zones have preferentially developed subparallel to them. The large-scale structural features in this area, therefore, can be explained in terms of an E-W compression acting over a protracted period of time.

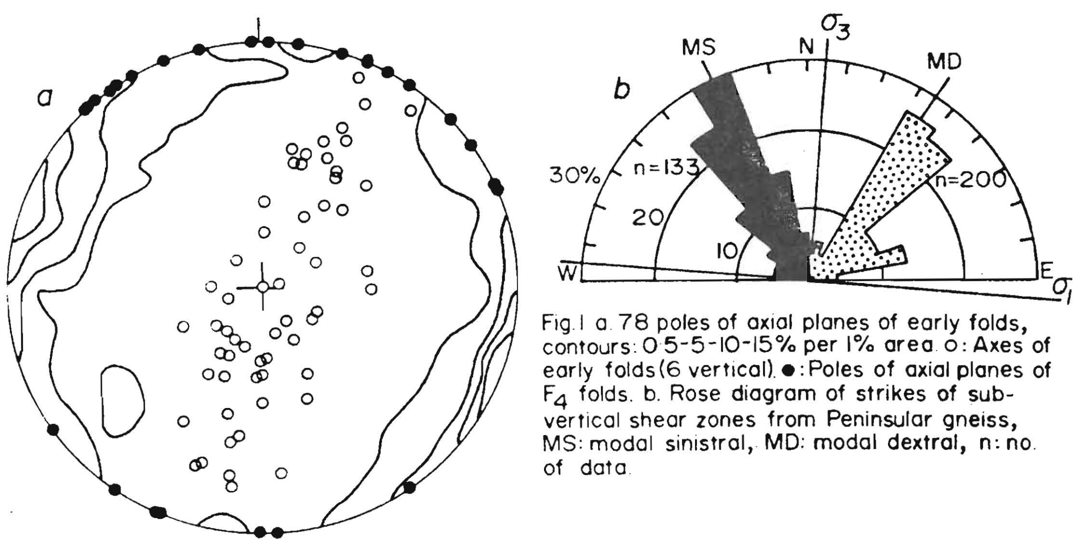

Fig. 1 a. 78 poles of axial planes of early folds, contours: 0.5-5-10-15% per 1% area. o: Axes of early folds (6 vertical). ●: Poles of axial planes of F_4 folds. b. Rose diagram of strikes of sub-vertical shear zones from Peninsular gneiss, MS: modal sinistral, MD: modal dextral, n: no. of data.

METAMORPHISM OF CORDIERITE GNEISSES FROM EASTERN GHAT GRANULITE TERRAIN, ANDHRA PRADESH, SOUTH INDIA ; D.S.N. Murthy and S. Nirmal Charan National Geophysical Research Institute Hyderabad 500 007 India.

Cordierite-bearing metapelites of the Eastern Ghat granulite terrain occur in close association of Khondalites (Garnet-sillimanite gneisses), quartzites, calc-silicate rocks and charnockites. The present study is limited to the rocks occurring between Bobbili in the north and Guntur in the south of Andhra Pradesh.

Cordierite-garnet-biotite-sillimanite-quartz-ilmenite $\pm$ spinel $\pm$ plagioclase $\pm$ hypersthene $\pm$ K-feldspar $\pm$ corundum $\pm$ anthophyllite form the mineral assemblage of these rocks. The association of the mineral and their textural relationship suggest the following metamorphic reactions: (i) Garnet + sillimanite + quartz = cordierite, (ii) hypersthene + sillimanite + quartz = cordierite, (ii) hypersthene + sillimanite + quartz = cordierite, (iii) sillimanite + spinel = cordierite + corundum, and (iv) biotite + quartz + sillimanite = cordierite + K-feldspar. Generally the minerals are not chemically zoned except garnet-biotite showing zoning when they come in close contact with one another.

The potential thermometers are provided by the Fe-Mg distribution of coexisting biotite-garnet and cordierite-garnet. Temperature of $750° \pm 50°$ is estimated based on garnet-biotite geothermometry[1,2,3]. The temperature estimated from the cordierite-garnet thermometry[1,4] is $730° \pm 60°$ C.

Conflicting interpretation of the P/T dependence of these reactions involving cordierite are due to H_2O in the cordierite. The estimates of H_2O in cordierite are made[5] and pressure estimated at $P_{H2O} = 0$ is 5.3 ± 0.2 Kb, while $P_{H2O} = P_{Total}$ the maximum pressure obtained for the cordierite gneisses is 7.0 ± 0.3 Kb. The positive optic axis measured in cordierite of these rocks is indicative of participation of P_{CO2} in the metamorphic equation[6] suggesting the $P_{H2O} < P_{Total}$. The presence of alkali feldspar-quartz assemblage which is common in these gneisses will be constrained from melting only if H_2O activity is less than 0.5. The piezometric array inferred is convex towards the temperature array, indicating a rapid and isothermal crustal uplift probably aided by thrust tectonics.

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TECTONIC EVOLUTION OF THE WESTERN AUSTRALIAN SHIELD

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India and Western Australia were formerly contiguous parts of Gondwanaland. Both regions contain similar kinds of Precambrian rocks and this abstract presents an outline of the tectonic evolution of the cratons and orogenic belts of Western Australia. The outcrop of Precambrian rocks called the Western Australian Shield (Fig. 1) consists of two cratons >2.5 Ga, four orogenic belts active between 2.0 and 0.65 Ga, and less deformed sedimentary rocks ranging from 1.6 - 0.75 Ga.

The oldest components of the Yilgarn Craton (Fig. 1) are remnants of early gneiss terranes that occur along its western margin. The largest and best known is the Narryer Gneiss Complex which consists of two groups of quartzo-feldspathic gneiss: Meeberrie gneiss derived from 3.65 Ga monzogranite and Dugel gneiss derived from 3.4 Ga syenogranite. They contain inclusions of a 3.73 Ga gabbro-anorthosite complex and are tectonically interleaved with a former cover of siliceous metasedimentary rocks about 3.35 Ga old. The gneiss complex was deformed and metamorphosed in granulite facies about 3.3 Ga. It is in steep tectonic contact with granite-greenstone terrane that makes up most of the Yilgarn Craton. These terranes were juxtaposed, intruded by large volumes of granite sheets and intensely deformed about 2.7 Ga ago.

The Yilgarn granite-greenstone terrane consists of 3.0 - 2.9 Ga ultramafic and mafic volcanic rocks that formed as extensive submarine lava plains and local volcanic centres of mafic and felsic volcanic rocks. The volcanics were deformed in a horizontal tectonic regime, intruded by extensive sheets of granite 2.7 Ga ago and then deformed into large scale upright fold interference structures. Most of the granite-greenstone terrane is in greenschist or low amphibolite facies but deeper levels are exposed in the southwest where the rocks are in granulite facies. This tilting and erosion of the craton occurred before the widespread intrusion of high-level plutons ranging from tonalite to granite about 2.6 Ga ago. These plutons are associated with major transcurrent shear zones and faults and the massive mobilization of gold which was concentrated in these structures.

The Pilbara Craton (Fig. 1) also consists of granite-greenstone terrane but most formed 3.6 - 3.0 Ga ago and is deformed and metamorphosed in greenschist facies. It is overlain with marked unconformity by 2.8 Ga Fortescue basaltic volcanics and intruded by tin-bearing granites 2.7 - 2.6 Ga ago. The Fortescue volcanics are conformably overlain by the 2.4 Ga iron formations of the Hamersley Basin.

The collision of the Pilbara and Yilgarn Cratons about 2.0 - 1.8 Ga ago led to the intervening Capricorn Orogen (Fig. 1). Collision began in the east where a thick slab of granitic basement was obducted onto the margin of the Pilbara Craton and adjacent rocks of the Hamersley Basin were folded and transported northward on thrusts. Uplift and erosion led to the infilling of a foreland basin subsequently deformed and metamorphosed in greenschist facies. At the southern margin of the orogen a sheet of imbricated mafic and ultramafic schists was obducted onto the Yilgarn Craton and over-ridden by thrust sheets of metasedimentary rocks and

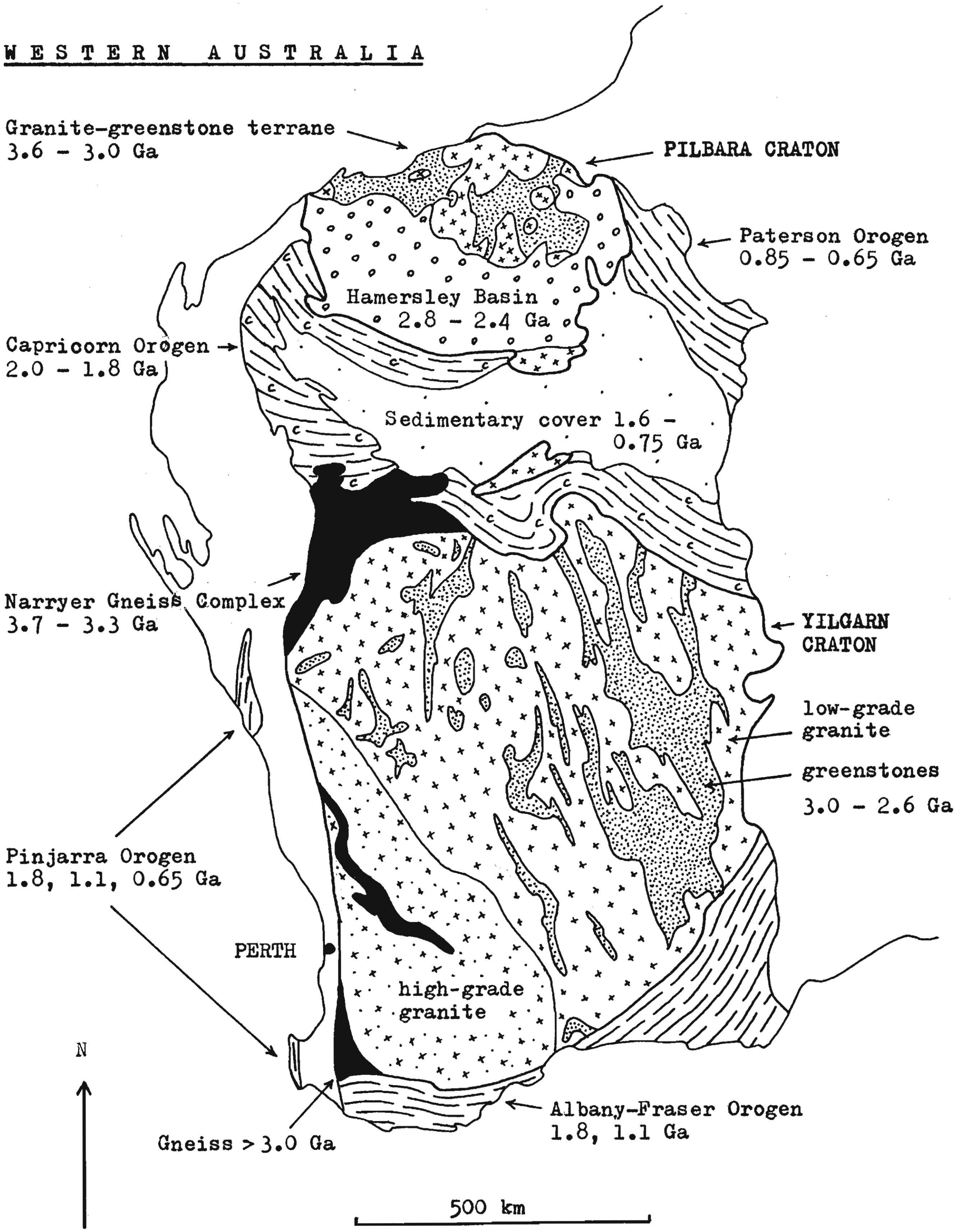
WESTERN AUSTRALIA
Granite-greenstone terrane
3.6 - 3.0 Ga
PILBARA CRATON
Paterson Orogen
0.85 - 0.65 Ga
Hamersley Basin
2.8 - 2.4 Ga
Capricorn Orogen
2.0 - 1.8 Ga
Sedimentary cover 1.6 - 0.75 Ga
Narryer Gneiss Complex
3.7 - 3.3 Ga
YILGARN CRATON
low-grade granite
greenstones
3.0 - 2.6 Ga
Pinjarra Orogen
1.8, 1.1, 0.65 Ga
PERTH
high-grade granite
N
Gneiss > 3.0 Ga
Albany-Fraser Orogen
1.8, 1.1 Ga
500 km

Fig. 1

gneissose granites. The inferred suture between the cratons is marked by a wide belt of granite plutons associated with a variety of mineral deposits.

Orogenic belts also developed along the southern and western margins of the Yilgarn Craton 2.0 - 1.8 Ga ago. In the south the Albany-Fraser Orogen (Fig. 1) incorporates both Archaean and early Proterozoic rocks and was substantially reworked about 1.1 Ga ago. It consists of a northern belt of low grade metasedimentary rocks thrust northward onto the craton. To the south are tectonic slices of intensely deformed lower crustal rocks (metagabbros and quartzo-feldspathic gneisses in granulite facies), and then a belt of Proterozoic ortho- and paragneisses in amphibolite facies intruded by sheets of 1.1 Ga granite. The southern margin of the orogen may lie in Antarctica.

Most of the Pinjarra Orogen to the west of the Yilgarn Craton (Fig. 1) is buried beneath about 10 km of sedimentary rocks which filled a rift valley 430 - 130 Ma ago that preceded the separation of the Indian subcontinent from Australia. In addition to tectonic and plutonic avtivity about 1.8 and 1.1 Ga the southern part of this orogen was reactivated about 650 Ma when a new plutonic complex of anorthosite and granite was deformed and metamorphosed in granulite facies and the adjacent craton was cut by faults, shear zones and pegmatites.

A fourth orogen (Paterson Orogen, Fig. 1) developed 850 - 650 Ma ago along the eastern margin of the Pilbara Craton. Thrust sheets of late Precambrian sedimentary rocks and older basement gneiss were transported southwestward, and the orogen may reflect the collision of the Western Shield with central and northern Australia.

STRUCTURAL RELATIONS OF CHARNOCKITES OF SOUTH INDIA

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Three temporal relations of charnockites are discernible in the Precambrian metamorphic terrane of Karnataka, Kerala, and Tamil Nadu in south India. The first of these is represented by foliated charnockites which are involved in isoclinal folds with attenuated limbs and thickened hinges. These charnockites have been boudinaged in the limbs of folds at places, with quartzofeldspathic veins in the boudin necks. They have been affected by near-coaxial open folds locally, followed by a ubiquitous set of upright folds with axial planes striking between NNW and NNE. The style and sequence of structures in the charnockites are identical with those in the gneissic host and the adjacent supracrustal rocks of varying metamorphic grade.

The second type of relation is shown by the charnockites which have been affected by migmatization synkinematic with the isoclinal first folding. This has led first to hypersthene-hornblende gneiss, and finally to hornblende-biotite gneiss, which is indistinguishable from the Peninsular gneiss <u>sensu</u> <u>stricto</u>.

The third situation-- exemplified by the outcrops of Kabbaldurga in Karnataka, around Krishnagiri in Tamil Nadu, and near Ottapalam in Kerala-- is depicted by the incipient charnockites formed in the low-pressure zones of fold-hinges and boudin-necks, and along the shear zones and axial planes of later folds in a migmatitic milieu. These are the charnockites developed from migmatitic gneisses at a late stage. Significantly, some of these charnockites show an axial planar foliation of later generation, without any trace of postcrystalline deformation.

Unless the folds of various generations represent different stages of a progressive deformation-- a contention running counter to the antipathic strain patterns registered by the isoclinal first folds and the non-coaxial later folds-- charnockites of south India must have evolved in at least two, if not three, distinct phases.

LOW- TO HIGH-GRADE METAMORPHIC TRANSITION IN THE SOUTHERN PART OF KARNATAKA NUCLEUS, INDIA ; S.M. NAQVI National Geophysical Research Institute, Hyderabad 500 007 INDIA

The southern part of Karnataka Nucleus is an area in which there is a strong imprint of 2.6 Ga metamorphism. This has affected the schist belts of Karnataka Nucleus from greenschist to upper amphibolite facies. The higher grades of metamorphism can be seen in the Holenarasipur, Nuggihalli, Krishnarajpet, Hadnur and Melkote schist belts in the southern part of Karnataka. In the high grade transition zone, around Sargur only keels of schist belts are preserved and occur as highly dismembered, disconnected belts with the top and bottom of the stratigraphic column obliterated due to high grade metamorphism and accompanying migmatization. Absence of high-grade metamrophic minerals as detrital heavies in the sediments of the Dharwar schist belts supports the contention that high grade metamorphism post-dated the Dharwar sedimentation and occurred around 2.6 Ga ago. Sargur type metamorphism (intermediate pressure) occurred at upper crustal levels where P H_2O was higher and charnockite type metamorphism occurred in lower crustal levels where P CO_2 exceeded P H_2O. Metamorphism in the two crustal levels apparently took place simultaneously. The Sargur Group of rocks are composed of sediments characteristic of platformal assemblages. The P-T conditions for the mineral assemblage in metapelites of Sargur Group indicate burial depths upto at least 15 km suggesting that they were subducted and later obducted during the development of Early Proterozoic Mobile Belt along the southern border of the Karnataka Nucleus.

PETROLOGY AND PHYSICAL CONDITIONS OF METAMORPHISM OF CALC-SILICATE ROCKS FROM LOW- TO HIGH-GRADE TRANSITION AREA, DHARMAPURI DISTRICT, TAMIL NADU; **B.L.Narayana, R. Natarajan and P.K.Govil,** National Geophysical Research Institute, Hyderabad-500 007 India

Calc-silicate rocks comprising quartz, plagioclase, diopside, sphene, scapolite, grossularite-andradite and wollastonite occur as lensoid enclaves within the greasy migmatitic and charnockitic gneisses of the Archaean amphibolite- to granulite-facies transition zone in Dharmapuri district, Tamil Nadu. They are associated with magnetite-quartzites and corundum- sillimanite-bearing metapelite bands in which segregation of leucosomes containing garnet and K-feldspar are present. The calc-silicate rocks are characterized by the absence of K-feldspar and primary calcite, presence of large modal quartz and plagioclase and formation of secondary garnet and zoisite rims around scapolite and wollastonite.

The mineral distributions suggest compositional layering. Late retrograde rim garnet at the interfaces of plagioclase and wollastonite is grossular-rich ($Gross_{72}$) while the other garnet is comparatively low in graossular content indicating variation in the bulk composition of different layers. Microprobe analyses of the constituent minerals in three calc-silicate rocks have shown that calcic-rich plagioclase (An_{88-89}) is associated with scapolite of lower equivalent anorthite content (eq. An_{67-73}) while less calcic plagioclase (An_{55}) is associated with scapolite of higher equivalent anorthite content (eq. An_{64}) indicating the control of bulk composition. The chemical composition and mineralogy of the calc-silicate rocks indicate that they were derived from impure silica-rich calcareous sediments whose composition is similar to that of pelite-limestone mixtures.

From the mineral assemblages the temperature, pressure and fluid composition during metamorphism have been estimated. The partitioning of Na and Ca between scapolite and plagioclase yield temperatures greater than 660°C[1] while the scapolite composition indicates a minimum temperature of less than 750°C. The garnet-clinopyroxene-plagioclase-quartz geobarometer[2] and clinopyroxene-plagioclase-quartz geobarometer[3] give pressures of about 6 kbars.

The observed mineral reaction sequences require a range of X_{CO2} values (from about 0.4 to 0.12) demonstrating that an initially CO_2-rich metamorphic fluid evolved with time towards considerably more H_2O-rich compositions. These variations in fluid composition suggest that there were sources of water-rich fluids external to the calc-silicate rocks and that mixing of these fluids with those of calc-silicate rocks was important in controlling fluid composition in calc-silicate rocks and some adjacent rock types as well. Probably the calc-silicate rocks behaved as an open system for a short time only, and the reactions resulting from rehydration proceeded more rapidly, and never completed.

PETROLOGY AND P-T CONDITIONS OF CALC-SILICATE ROCKS
Narayana, B.L. et al.

Hydration causing formation of garnet and zoisite rims in calc-silicate rocks is related to secondary biotite in the associated charnockitic gneisses. The occurrence of leucosome segregations with garnet and K-feldspar in metapelites indicates melting and absorption of H_2O into anatectic melts and this dehydration has aided the granulite-facies metamorphism of the South Indian shield in addition to streaming of CO_2-rich fluids[4] proposed for the metamorphism.

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NATURE AND ORIGIN OF FLUIDS IN GRANULITE FACIES METAMORPHISM:

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Orthopyroxene, the definitive mineral of the granulite facies, may originate in prograde dehydration reactions in rock systems open to fluids or may be a premetamorphic relic of igneous intrusions or their contact aureoles which persisted through fluid-deficient metamorphism. Terrains showing evidence of open-system orthopyroxene-forming reactions are those of South India and southern Norway. An example of fluid-deficient granulite facies metamorphism is the Adirondack Highlands of New York, where metamorphic pyroxene commonly resulted from dry recrystallization of pyroxenes of plutonic charnockites and anorthosites. The metamorphism recorded by the presence of orthopyroxene in different terrains may thus have been conservative or may have involved fluids of different origins pervasive on various length-scales.

Metamorphism with pervasive metasomatism is signaled by monotonous H_2O, CO_2 and O_2 fugacities over large areas, nearly independent of lithology, by scarcity of relict textures, and by pronounced depletion of Rb and other large ion lithophile (LILE) elements in the highest grade areas, such as the southernmost part of the Bamble, South Norway, terrain (1). Primary hornblende is rare or absent in quartzofeldspathic gneisses and orthopyroxene is ubiquitous in acid and basic rocks in the charnockitic terrains. Pronounced major and minor element redistributions took place during metasomatic charnockitization of amphibole gneiss at Kabbaldurga, Karnataka (2).

Conservative metamorphism of originally dry rocks in the Adirondacks is evidenced by incipient grain-boundary garnet-forming reaction zones between plagioclase and interstitial pyroxene in anorthosites, implying lack of a pervasive flux, by elevated ^{18}O of paragneisses, reflecting preservation of low-temperature processes in the protoliths, by strong lateral gradients in ^{18}O (3) and in apparent volatile fugacities, especially $f(O_2)$, implying lack of a large oxygen source in the form of pervasive H_2O or CO_2, and by common preservation of upper-crustal, premetamorphic textures, such as chilled margins of dikes, rapakivi texture, and thermal aureoles around intrusions. Lack of LILE depletion in high-grade granulites indicates fluid-deficient metamorphism.

The origin of fluids is a key issue in high-grade metamorphism. Such fluids must have been low in H_2O to coexist with orthopyroxene. Dense CO_2-rich fluid inclusions in Bamble (4) and the Nilgiri Hills (5) suggest that fluids were dominantly carbonic in metamorphism of the charnockitic terrains. Such fluids could have resulted from: A) alteration of resident pore fluids by absorption of H_2O into anatectic melts (6); B) exsolution from crystallization of deep-crustal mafic (4) or intermediate (7) magma bodies; C) decarbonation of crustal limestones and dolomites (8); D) an outgassing mantle hot spot (9); E) reaction of hydrous minerals and graphite in uplift and decompression of granulite-facies (10); or F) release of CO_2 from deep crustal fluid inclusions by deformation during a metamorphic episode (2). Occurrence of orthopyroxene in migmatitic leucosomes in Namaqualand, South Africa (11) is evidence for A); charnockitic margins on acid dikes in the Wind River Range of Wyoming (12) is evidence for B); massive charnockite grading upward to patchy charnockite in hornblende gneiss overlying a massive marble bed in Sri Lanka is evidence for C) (13); the large length-scales and high paleotemperatures nearly independent of paleopressures in the South India terrain suggest a subcrustal origin of heat-transporting fluids in accord with D) (9); apparent fracture control of charnockitic alteration of paragneisses in Kerala suggest E) (10); and late Archaean charnockitic veins around the margins of possibly older granulites in southern Karnataka suggest F) (2).

It is likely that different kinds of fluids of different origins and in varying amounts were instrumental in different granulite terrains. Resolution of the nature and extent of the operation of fluids in granulite metamorphism will be provided by detailed studies of oxygen isotopes, oxidation states of iron oxides and silicates, apparent paleofugacities of H_2O and CO_2 indicated by mineral assemblages, and by open-system versus closed-system behavior indicated by metamorphic patterns of major and trace elements.

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ACCRETIONARY ORIGIN FOR THE LATE ARCHEAN ASHUANIPI COMPLEX OF CANADA;
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At 300 x 300 km, the Ashuanipi complex is one of the largest massif granulite terranes of the Canadian Shield (Fig. 1). It makes up the eastern end of the 2000-km-long, lower-grade, east-west belts of the Archean Superior Province (1), permitting lithological, age and tectonic correlation (2). Numerous lithological, geochemical and metamorphic similarities to south Indian granulites suggest common processes and invite comparison of tectonic evolution.

Superior Province consists of a northern high-grade region, the Minto block (Fig. 1), and the well-known southern subprovinces of 3.1-2.7 Ga greenstone-granite, metasedimentary gneiss and plutonic character (1). Metasedimentary gneiss probably extends, through poorly-known territory, from the east-striking belts into the Ashuanipi complex (1,3).

Several gneissic and homogeneous lithological units are recognized on the regional scale in the Schefferville area (3,4). Paragneiss, consisting of assemblages of Grt-Opx-Bio-Plg-Qtz±Kfs, is the oldest. Although mainly psammitic, it has rare compositional variation to pelite and leptynite. Interlayered with paragneiss on the m to km scale is early tonalite, with characteristic igneous oikocrystic orthopyroxene (5), variably broken down to biotite and metamorphic orthopyroxene during deformation and migmatization. It varies compositionally to rare diorite and gabbro. Layered pyroxenite-peridotite sills, up to 80 m thick, with rare associated gabbro, occur as strings of boudinaged pods up to 10's of km long.

Homogeneous intrusions make up some 90% of the terrane. The oldest bodies are foliated Opx-Bio±Cpx±Hbl tonalite, quartz diorite and diorite. These are cut by the most abundant rock type of the complex: coarse-grained to megacrystic Grt-Opx-Bio-Plg-Qtz-Kfs granodiorite, mapped as homogeneous diatexite (3,4,6) because of its association with, and compositional similarity to paragneiss. Two texturally similar units are recognized: an older, more voluminous, garnet-bearing variety, and younger pods, layers and plutons without garnet. Massive to weakly foliated Cpx-bearing granite and syenite, locally with nepheline, form the youngest intrusions.

The dominant structural elements are an S_1 migmatitic layering in gneisses and foliation in homogeneous intrusions that defines a NE-dipping homocline on the regional scale. Open, upright F_2 folds of S_1 layering form discontinuous, east-plunging or doubly-plunging structures, generally basins, on the 10-20 km scale. The folds are localized in large-scale, open "Z" warps of regional foliation, possibly related to dextral transcurrent movement. Narrow concordant shear zones are accompanied by abundant migmatitic leucosome, Grt, Opx-bearing pegmatite, and late, brittle fractures. Diatexite contains inclusions of migmatitic (S_1) gneiss, but some concordant bodies are folded with gneiss in F_2 structures, bracketing intrusion between D_1 and D_2.

The assemblage Grt-Opx-Bio-Plg-Qtz-Kfs is ubiquitous in the Schefferville region, in paragneiss, diatexite, some early tonalites, and in late pegmatites. One occurrence of Grt-Crd-Sil-Bio-Plg-Qtz-Kfs has been recognized. Mafic rocks have Opx-Cpx-Hbl-Plg±Qtz. Two generations of orthopyroxene are present locally in early tonalite: igneous oikocrysts and blocky, metamorphic porphyroblasts surrounded by mafic depletion haloes. Minerals are fresh and yield Grt-Bio temperatures for paragneiss and diatexite in the 750-800°C range using (7). Based on Grt-Opx-Plg-Qtz barometers (8,9), metamorphic pressure was in the 5 to 6.5 kb range. Whole-rock geochemical analyses of migmatitic rocks show no evidence of Rb depletion with respect to K (avg K/Rb ratio of 210). Patchy retrogression of Opx and Grt to Bio is common in the western part of the complex (10,2).

Diatexites are uniformly coarse-grained, have sharp, concordant contacts with adjacent gneiss, and contain angular to lenticular gneissic inclusions, suggesting intrusive emplacement into gneiss at the present structural level. Garnet-bearing diatexite is very similar to paragneiss in terms of mineralogy, mineral chemistry, major, trace and rare-earth element chemistry (Fig. 2) and may thus represent the fused equivalent of paragneiss. REE abundances and patterns are comparable for early tonalite, paragneiss and diatexite. Tonalites and diatexites have higher K/Rb ratios than gneisses (290, 257 respectively), possibly indicating igneous fractionation (11).

Zircon and monazite U-Pb ages (2) constrain the plutonic and metamorphic history. Early tonalites have discordant zircons with minimum ages greater than 2.7 Ga whereas a foliated tonalite pluton is 2.69 Ga. Diatexites have some inherited zircon; igneous grains give 2.67-2.66 Ga. Monazite from late pegmatite is 2.65 Ga, similar to the regional monazite cooling ages in gneiss and diatexite. A zircon date of 2.642 Ga on retrogressed diatexite, distinctly younger than monazite cooling ages, suggests that a discrete, late, localized hydrothermal event caused the retrogression (2). The small age gap between zircon and monazite ages indicates that cooling began quickly after the metamorphic peak. Proterozoic sediments of 2.15 Ga age overly the granulites unconformably, supporting this inference.

Critical parameters to consider in interpreting the origin of the complex include: 1) supracrustal rocks are paragneiss, derived from homogeneous, immature clastic metasediments; 2) most of the complex is made up of intrusive rocks, dominantly diatexite, generated, emplaced and crystallized during the high-grade metamorphism, at 2.67-2.66 Ga, at the same time as granite plutonism in along-strike low-grade belts to the west (12); 3) metamorphic pressures are moderate to low for granulites (17-22 km erosion level); cooling and erosion began quickly after metamorphism; 4) melting was the dominant process during granulite metamorphism, producing migmatitic textures in gneiss and generating diatexite melts at depth.

Based on observations at the 17-22 km erosion level in the Ashuanipi complex and 8-15 km levels exposed in belts to the west, a model of metamorphic development in a >2000 km accretionary prism is proposed (Fig. 3): immature sediments derived from adjacent arcs (greenstone belts) were accreted and thickened to a maximum 55 km (13) at 2.75-2.70 Ga. Thermal relaxation and/or arc magmas (14) heated the lowermost crust, causing fusion and upward heat transfer through granitic magmatism. Magmas crystallized as deep-crustal charnockites (diatexite) and fractionated (15) to form higher-level peraluminous granite (12). The overthickened crust rebounded to an isostatically stable 35 km by erosionally removing the upper 8-22 km. Post-metamorphic erosion-level differences along the belt may be related to the amount of early structural thickening. Similar features characterize some Cenozoic accretionary complexes in the N. American Cordillera (14,16).

Diatexite, which forms the bulk of the Ashuanipi complex (17), is similar to S. Indian "Ponmudi-type"(18) charnockite in terms of texture, mineralogy, composition and crystallization conditions, but probably crystallized to granulite-facies assemblages directly from a melt. Before comparing models of tectonic evolution, the age of Indian charnockitization with respect to regional metamorphism, plutonism and crustal formation should be documented by precise U-Pb studies.

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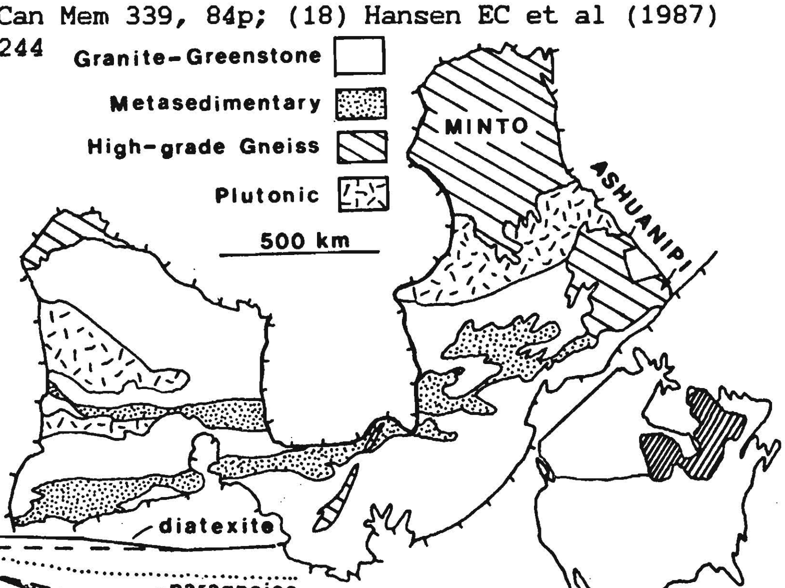

Fig. 1: Superior Province (1) showing Ashuanipi complex in relation to E-W subprovinces.

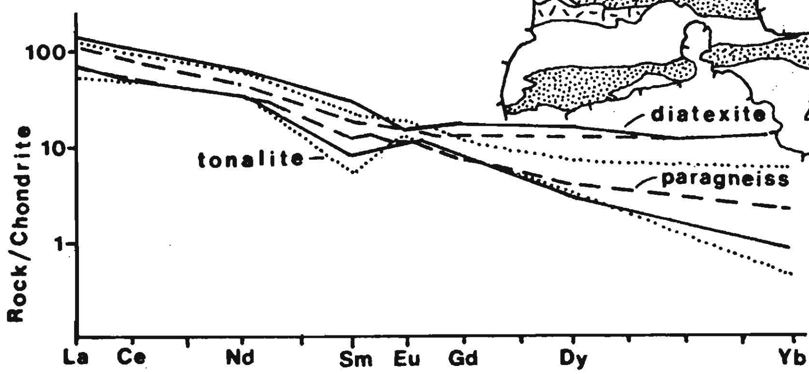

Fig.2: Chondrite-normalized REE patterns showing similarity among major rock types.

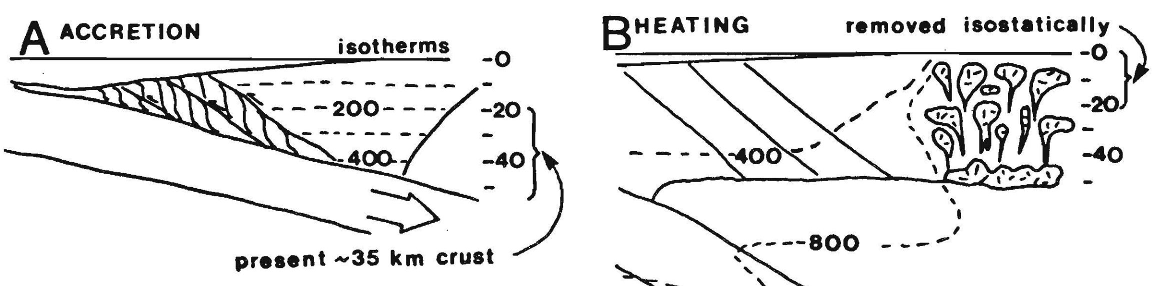

Fig.3: Accretionary model for (A) construction of a 55-km thick sedimentary crust, later heated (B), fused and thinned by erosion.

TECTONIC IMPLICATIONS OF ARCHEAN ANORTHOSITE OCCURRENCES

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Introduction

Anorthositic complexes occur in essentially all Archean cratons and contain large equidimensional plagioclase crystals (up to 30cm. diam.) with highly calcic compositions (An_{80} to An_{90}). Several occurrences have been described in India [1],[2],[3],[4]. Because the anorthositic complexes represent cumulates, the composition and source of parental melts has been a longstanding problem. Plagioclase having the same composition and texture as that in anorthosites also occurs as megacrysts in basaltic flows, dikes, and sills in which the crysts may be scattered or concentrated in lenses or trains. We suggest that the anorthosites and megacrystic basalts are petrogenetically related. However, the tectonic settings for these occurrences appear to be quite variable suggesting that several environments may be represented. A brief outline of the regional settings of these anorthosites and petrogenetically related basalts follows.

Archean Occurrences of Megacrystic Anorthosites

1. Cumulate crystal segregations in anorthositic to gabbroic complexes associated with volcanic sequences typical of low to middle metamorphic grade greenstone belts [5],[6].
2. Cumulate crystal segregations in thick anorthositic to gabbroic sills that intrude volcanic sequences typical of greenstone belts [7].
3. Cumulate crystal segregations in anorthositic to gabbroic complexes associated with high grade metamorphic terrains containing marbles, quartzites, quartzofeldspathic gneisses, and amphibolites [3],[8].

Archean Occurrences of Megacrystic Basalts

1. Flows, dikes, and sills in volcanic sequences typical of greenstone belts [9],[10].
2. Dike swarms in stable cratonic areas forming parallel to subparallel patterns over hundreds of thousands of square kilometers intruding both high grade granitic gneisses and low to middle grade supracrustal belts [10].

Younger Occurrences

Similar occurrences of megacrysts in basalts of early Proterozoic age are known in cratonic dikes of the Bighorn Mountains of Wyoming [11] and the Beartooth Mountains of Montana [12] and in volcanic flows of the Bell Island Group of the Northwest Territories [13]. Recent occurrences of similarly calcic plagioclase phenocrysts are known in oceanic volcanic flows at spreading ridges, hotspots, aseismic ridges and fracture zones [14]. However, these normally involve only small phenocrysts up to a few millimeters in size and usually are more lathy than equidimensional in shape. In contrast to these common oceanic occurrences, volcanic flows over the Galapagos hotspot display more equidimensional calcic crysts up to 3cm. across [15]. In essentially all of the Archean and Proterozoic occurrences the distribution coefficients for REE's indicate equilibrium between the megacrysts and their matrices of Fe-rich tholeiites [16]. However, use of the same distribution coefficients in the more recent occurrences indicates substantial disequilibrium between the crysts and their tholeiitic matrices. Thus, the more recent occurrences of calcic plagioclase crysts require an additional stage of evolution before reaching their current environment, thereby providing a bit more uncertainty about their petrogenesis than the older occurrences and making direct comparison with ancient tectonic environments untenable.

Melts and Magma Chambers

Utilizing experimental petrologic studies of the basaltic matrices and distribution coefficients with trace element analyses of plagioclase it seems clear that all of the above-listed megacryst occurrences are associated with similar parent melts for both the anorthosites and megacrystic basalts [**16**]. The melts are relatively Fe-rich, tholeiitic basalts that exhibit a significant range of Fe-enrichment (50-70% on an AFM plot) in association with the megacrysts. The basalts of the cratonic dikes are more enriched in K, Na, and light REE than their greenstone counterparts but follow a parallel Fe-enrichment trend. Furthermore, the fractionation trends and formation of the crysts occurred at relatively shallow levels (<5Kb) [**16**]. The megacrysts in all of the occurrences are quite uniform in composition (±1 to 2 An units) over several centimeters except for very thin rims (~100-200μm). This suggests nearly isothermal crystallization at a nearly constant melt composition over substantial periods of time. Geochemical modeling of trace elements and subtle cyclic compositional trends in the plagioclase indicate multiple influxes of melts into the magma chambers during evolution of the melts and growth of the megacrysts. The widespread occurrences of the megacrystic units in both greenstone belts and huge cratonic dike swarms further suggests extensive development of magma chambers in which tholeiitic melts produce calcic plagioclase as a major liquidus phase under both cratonic and oceanic Archean crusts. In essentially all occurrences where adequate preservation of initial igneous textures and structures exists, there is evidence for at least two stages of plagioclase formation. In the anorthositic complexes there are bimodal units in which very large crysts are mixed with smaller, but still large, crysts. In the basalts the calcic megacrysts have thin sodic rims that match the composition of the lathy plagioclase in the matrices. Both situations indicate formation of the large crysts at locations other than their final position of emplacement, probably indicating a complex series of magma chambers in the crust.

Crustal Levels

The anorthosites appear to have intruded at various crustal levels. In many of the low-grade supracrustal (greenstone) settings the preservation of primary sedimentary and volcanic structures and textures indicate that the regions have always been at low grade and that the anorthosites intruded at very shallow levels. In the higher grade occurrences it is not always clear whether the anorthosites intruded at the higher grades or at low grade and were later upgraded. In Manitoba there is a clear case of anorthosites initially intruding low grade supracrustal units but later a regional metamorphic gradient produced a continuous sequence from low greenschist to granulite grades in all of the units [**17**]. In the granulite grade Shawmere anorthosite complex of Ontario [**18**], however, there are some nearly undeformed enclaves where the more mafic units contain well preserved olivines and pyoxenes with well preserved exsolution texture. Furthermore, some plagioclase contains well preserved polysynthetic twinning that looks like original igneous twinning. Such preservation seems unlikely if the anorthosite were intruded at low grade and underwent progressive metamorphism to granulite grade, unless the system were essentially dry during metamorphism which also seems unlikely in view of the biotite- and amphibole-bearing units adjacent to the intrusion and amphibole-bearing pegmatitic zones within the complex.

Effects of Fluids at High Grades

Several petrographic observations in high-grade anorthositic complexes indicate the infiltration of substantial amounts of fluid. Recrystallized plagioclase ranging from strained patchy areas to polycrystalline areas may occur as irregularly distributed zones, vein-like stringers, or rims around relict cores. Generally these areas display elevated values of Na and REE's in the plagioclase. Inclusions of tiny amphibole needles are common in non-recrystallized plagioclase of upper greenschist and higher grades. Concentration of the inclusions is highly variable even within a single crystal. Many plagioclase crysts contain 10% or more by volume of these inclusions. The initial FeO content of the plagioclase is in the .4-.6% range and the FeO content of inclusion-rich plagioclase is ~.1%. However, microprobe analyses of the amphiboles indicate 15-20% FeO which for 10% inclusions requires several times more FeO than was present in the initial plagioclase. Similarly the heavy REE contents of these plagioclase separates are substantially increased over the initial values reflecting the heavy REE enrichment in amphiboles. Clearly there must be flow of fluids through the plagioclase in some manner to add Na, Fe, heavy REE, and H_2O.

Conclusions for Archean and early Proterozoic Megacrystic Units

1. Segregations of plagioclase may occur at various depths in the crust to form anorthosite.
2. Anorthosites may occur in oceanic volcanic crust and in cratonic or shelf environments.
3. Megacrystic basalts may form in oceanic or stable cratonic environments.
4. Plagioclase megacrysts in Fe-rich tholeiites indicate relatively shallow magma chambers.
5. Large uniform crysts require extensive periods of isothermal growth at nearly constant melt composition and almost certainly formed in fractionating magma chambers that are periodically replenished.
6. Megacrystic tholeiitic dike swarms indicate widespread replenishing magma chambers under stable cratons.
7. It is not clear what oceanic environment is represented by megacrystic units in greenstones but it does require magma chambers for substantial time at similar temperatures and melt compositions over extensive areas.
8. Petrogenetic conditions for formation of megacrystic anorthosites and basalts in the Archean and early Proterozoic were not the same as in younger times.
9. Substantial flow of fluids accompanied by exchange of components can occur in anorthosites at high grades of metamorphism with little more effect on the plagioclase than formation of amphibole inclusions and scattered recrystallization.

In summary, megacrystic anorthosites and basalts can occur in a variety of geologic settings and by themselves are not definitive. Only with additional field, petrologic and geochemical data can the settings be understood.

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METAMORPHIC CONDITIONS IN THE NILGIRI GRANULITE TERRANE AND THE ADJACENT MOYAR AND BHAVANI SHEAR ZONES: A REEVALUATION

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The Nilgiri Hills massif, a tilted and uplifted segment of late Archaean crust is made up of garnet and hypersthene-bearing enderbitic to charnockitic rocks with layers and bodies of mafic pyroxene-plagioclase rocks with or without garnet and enclaves of pyroxenitic rocks. Granulite facies metamorphism occurred about 2.5 Ga ago and closely followed the emplacement of the igneous protoliths (1). The crustal segment of the Nilgiri Hills evidently represents an early Proterozoic addition to the Archaean Dharwar craton in the north, and the separating Moyar shear zone a major suture zone. The Bhavani shear zone to the south, on the other hand, is regarded as reworked Nilgiri-type crust. High-grade metamorphism in the Bhavani and Moyar shear zones and the adjacent Dharwar craton is coeval with the granulite facies event in the Nilgiri Hills massif (1,2,3).

Previous estimates of metamorphic conditions in the Nilgiri Hills and adjacent shear zones indicate temperatures between 700 to 850 ^{o}C and pressures of 7 to 10 kb (2,4,5,6,7). Only recently it has been pointed out (8) that the calibrations of garnet-pyroxene thermometers and garnet-pyroxene-plagioclase-quartz barometers employed in these studies, are afflicted with erroneous assumptions regarding mixing properties of the ferromagnesian phases. It is likely, therefore, that much of the scatter in the reported P-T data is an artifact of variations in the bulk chemistry of the rocks.

To derive improved estimates of metamorphic conditions in the Nilgiri block and the adjacent shear zones and to assess spatial P-T gradients with more confidence, an up-dated reevaluation of P-T-X_{fl} conditions was carried out. It is exclusively based on critically revised and internally consistent thermometers and barometers and on an extensive set of mineral composition data from more than 60 garnet-pyroxene-bearing rock specimens of wide-ranging composition. Only core compositions of the coexisting phases were used in the computations and the P-T estimates are thought to reflect near-peak conditions of granulite facies metamorphism. The temperature data calculated with several Fe-Mg exchange thermometers (gar-cpx, gar-opx, gar-bio, opx-bio) are in agreement and indicate almost isothermal equilibration at 730 + 30 ^{o}C in the entire Nilgiri block and the adjacent shear zones. The pressure data obtained from gar-opx-plag-qtz barometry document a continuous regional gradient from about 7.5 -- 8 kb in the Bhavani shear zone to 8.7 -- 9.2 kb in the northern margin of the Nilgiri block and the Moyar shear zone. The abrupt increase in pressure values at the northern margin of the Nilgiri Hills reported by earlier workers (6,7) does not exist and obviously resulted from the effects of bulk chemistry on the barometric calibrations. North of the Moyar shear zone, in the deepest part of the Dharwar craton, a similar P-T regime prevailed during upper amphibolite to granulite facies metamorphism (750 + 70 °C and 8 + 1 kb; cf. 2,6,9).

The abundance of high-density carbonic fluid inclusions (10) documents that the granulites in the Nilgiri crustal segment equilibrated in the presence of extremely CO_2-rich pore fluids. The homogenization temperature data (Th -52 to 19 °C; peak between -40 to -27 °C) and derived density values indicate fluid entrapment near peak metamorphic conditions. The source of fluids is not known. The absence of carbonate rocks and the rareness of graphite-bearing metasediments in the Nilgiri granulite terrane, however, suggests pervasive influx of carbonic fluids from deeper levels.

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GNEISS-CHARNOCKITE TRANSFORMATION AT KOTTAVATTAM, SOUTHERN KERALA (INDIA)

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At Kottavattam, leucocratic granitic garnet-biotite gneisses (age < 2 Ga) have been partially transformed to coarse-grained charnockite along a system of conjugate fractures (N70E and N20W) and the foliation planes (N60-80W; dip 80-90 SW) about 550 m.y. ago. (1). To examine and quantify changes in fabric, mineralogy, pore fluids and chemical composition, associated with this process, large rock specimens showing gneiss-charnockite transition were studied in detail.

The gneisses exhibit a streaky foliation defined by biotite, which is partly obliterated by a diffuse network of garnet-bearing leucosomes. This typical migmatic texture is completely extinguished in the charnockitized zones due to thorough recrystallization and considerable coarsening. Except of the partial breakdown of biotite and the neoblastesis of hypersthene, only minor changes in mineralogy and modal composition are observed (gneiss: kfsp 26-30, qtz 28-30, plag 22-27, gar 6-10, bio 6-10; charnockite: kfsp 27-30, qtz 24-28, plag 26-29, gar 6-10, bio 2-4, opx c.5). Ilmenite, pyrrhotite, graphite + rutile and magnetite occur in both the gneiss and charnockite, thus indicating a comparable internal buffering of pore fluids to low fugacities of water and oxygen, but to high fugacities of carbon dioxide. A comparable, though complex evolution of the pore fluids in gneiss and charnockite is also documented by their similar fluid inclusion characteristics (2): relic briny inclusions (+salt)--- medium- to low-density carbonic inclusions (0.70-0.86 g/cm^3; 4-10 mol% N_2, < 1 mol% hydrocarbons)---nitrogen inclusions (up to 14 mol% CO_2, < 1 mol% hydrocarbons) --- medium-density watery inclusions (0.89-0.94 g/cm^3) and mixed CO_2-H_2O inclusions forming clathrate ices.

The chemical data show that 'in-situ' charnockitization at Kottavattam was essentially an isochemical process:

	SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5
gn:	68.1	13.6	5.6	0.08	1.1	2.4	2.5	4.4	0.90	0.38
ch:	67.9	14.0	4.7	0.04	0.9	2.3	2.7	5.3	0.87	0.36

	Rb	Sr	Ba	Zr	V	Zn	La_N	Yb_N	Eu_N/Eu_N^*	$\delta^{18}O$
gn:	220	130	1055	344	105	65	132	32	0.2	10.3‰
ch:	216	141	1032	349	70	63	132	20	0.3	10.3

The compositions of mineral phases in the gneiss and charnockite assemblages are almost identical: garnets (alm 75-76, pyr 13-15, gro 7-9, spe 2), biotites (X_{Mg} 0,47-0.53; Ti 0.55-0.64 atoms p.f.u.), plagioclases (An 32-36, or 1-2), K-feldspars (Or 78-84, Ab 15-20, An 1-2), ilmenites (>98 $FeTiO_3$); orthopyroxenes could not be analysed due to complete alteration.

P-T estimates obtained from up-dated calibrations of garnet-biotite thermometry and garnet-plagioclase-quartz-ilmenite-rutile barometry indicate that equilibration of the gneiss and charnockite assemblages occurred at isothermal-isobaric conditions, i.e. 750 + 10 °C and 5.6 + 0.2 kb lithostatic pressure.

The results of the present study corroborate the concept that charnockite formation at Kottavattam is an internally-generated phenomenon (1) and was not triggered by the influx of carbonic fluids from a deep-seated source (3,4). We suggest that charnockitization was caused by the following mechanism:
(i) Near-isothermal decompression during uplift of the gneiss complex led to an increase of the pore fluid pressure ($P_{fluid} > P_{lith}$) which - in a regime of anisotropic stress - triggered or at least promoted the development of conjugate fractures.
(ii) The simultaneous release of pore fluids from bursting fluid inclusions and their escape into the developing fracture system resulted in a drop of fluid pressure ($P_{fluid} < P_{lith}$) which ultimately initated the dehydration reaction (i.e. the breakdown of biotite and neoblastesis of hypersthene).
(iii) The internal generation and buffering of the fluids and their probably limited migration in an entirely granitic rock system explains the absence of any significant metasomatic mass transfer, as oposed to the externally controlled Kabbaldurga-type charnockitization (4,5).

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KABBALDURGA-TYPE CHARNOCKITIZATION: A LOCAL PHENOMENON IN THE GRANULITE TO AMPHIBOLITE GRADE TRANSITION ZONE

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In the deeply eroded Precambrian crust of South India and Sri Lanka, a series of spectacular exposures shows progressive development of coarse-grained charnockite through dehydration of amphibolite grade gneisses in different arrested stages (1,2,3, 4,5,6).

At Kabbaldurga, charnockitization of Archaean grey biotite-hornblende gneisses (3.4 Ga; U-Pb zircon upper intercept data (7)) occurred about 2.5 Ga ago (U-Pb zircon lower intercept data and Rb-Sr whole rock isochron (7)) and evidently was induced by the influx of external carbonic fluids along a system of ductile shears and the foliation planes (3,4,6). The results of oxygen isotope thermometry (6) and of geothermobarometry in adjacent areas (8,9) indicate a P-T regime of 700-750 ^{o}C and 5-7 kb. The decrease of water activity in the fluid infiltrated zones caused an almost complete breakdown of hornblende and biotite and the new growth of hypersthene. Detailed petrographic and geochemical studies (6) revealed marked changes in mineralogy and chemistry from granodioritic to granitic which document the metasomatic nature of the process.

The marked gain in K, Rb, Ba and Si is attributed to intense replacement of plagioclase by K-feldspar through cation exchange with the passing fluids, whereas the loss of Fe, Mg, (Ca), Ti, Zn, V, P and Zr resulted from dissolution of hornblende, biotite, magnetite, apatite and zircon (6). A systematic depletion of the REE and especially the HREE in the charnockites which is attributable mainly to the progressive dissolution of zircon, led to strongly fractionated REE patterns with positive Eu-anomaly (La_N/Yb_N 20-80; Eu_N/Eu_N^* up to 1.8).

In the case of Kabbaldurga, an external source for the carbonic fluids is indicated by the fluid inclusion characteristics and stable isotope data (3,4,6). While most workers assume a generation of these fluids by deep-seated processes, e.g. degassing of underplated basaltic magmas, decarbonation of subducted sediments or the upper mantle (2,3,4), it is suggested here that the most likely source for the carbonic fluids is the 'fossil' reservoir of carbonic fluids trapped in the deeper crustal granulites underlying the gneiss terrane at Kabbaldurga. Shear deformation has tapped this reservoir and generated the pathways for fluid ascent.

The regional distribution of exposures with 'in-situ' charnockitization in southern India and Sri Lanka clearly indicates that this process was restricted to a zone transitional to the deeper and pervasingly granulitized crust. The evidences from Kabbaldurga and similar exposures in southern Kerala (5, 10) and Sri Lanka (4, 11) show that dehydration and the intensity of accompanying metasomatism were controlled by fluid-rock interaction in a system of tectonically generated fluid-pathways. Despite the differences in the mineralogy and chemistry of the precursor gneisses, the final product is always a coarse-grained massive hypersthene-bearing rock of granitic composition (charnockite s.str.). In all cases, 'in-situ' charnockitization was a late process which occurred well after the major event of penetrative deformation, high-grade metamorphism and migmatisation when during uplift the rheological properties of the rocks changed from ductile to brittle. Thus it appears unlikely that this type of charnockite formation caused the pervasive granulitisation of extensive parts of Precambrian lower crust in southern India and Sri Lanka.

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TECTONIC EVOLUTION OF THE ARCHAEAN HIGH-GRADE TERRAIN OF SOUTH INDIA

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The southern Indian shield (Fig. 1) consists of three major tectonic provinces viz., (1) Dharwar Craton, (2) Eastern Ghat Mobile Belt and (3) Pandyan Mobile Belt. An understanding of their mutual relations is crucial for formulating crustal evolution models.

Dharwar Craton is divisible into Western and Eastern Blocks separated by the linear Closepet Granite (1). The supracrustal belts of the Western Block are comparable to the Early Proterozoic 'geosynclines' of Canada and Australia and those of the Easter Block are typical late greenstone belts. Both types of N-S trending supracrustals are co-eval (2600 Ma) and their differences are due to minor reactivation of 3000-4000 Ma old basement in the Western Block, in contrast to the extensive juvenile plutonism and large scale crustal remobilization of the Eastern Block, resulting from anomalous heat flow from mantle. The favoured model for their evolution is sagging and rifting of sialic crust with proto-ocean opening and its partial closure due to regional compression (2). Still older supracrustals (Sargur Group) are found in the gneissic basement as small enclaves (3) and their origin is obscure.

Orthogonal to the trend of the supracrustal belts is the E-W trending charnockite belt extending from Madras to Mangalore (4). As the supracrustal belts approach this belt they become narrower, more highly metamorphosed and migmatised. Trains of supracrustal enclaves cut throught the charnockite belt and after passing through a series of small dextral shear zones (Kabini, Gundlupet, Moyar, Bhavani) are terminated by the major Palghat-Cauvery shear zone (5). Curving into this main shear zone are the numerous northerly vertical fault zones (Chitradurga, Bababudan). The faults are developed contemporaneously with the folding of Dharwar supracrustals and are fomed as a consequence of subhorizontal shortening and basement uplift to the east (6). The Palghat-Cauvery shear zone is marked by fissile gneisses containing roots of supracrustal belts and dismembered layered basic complexes. The high grade terrain occurring to the north of this shear zone represents deeper crustal levels of the Dharwar craton (7) brought up due to northerly tilt of the Peninsular shield during Himalayan collision.

<u>Pandayan Mobile Belt</u>: This terrain which lies to the south of the Cauvery shear zone is discinctly different from the Dharwar Craton and is divisible into two zones, the northern and southern. The northern zone consists essentially of the orthoquartzite-carbonate-pelite suite (with minor basics) within a migmatitic and charnockitic terrain. It has curving and swirling structural patterns like the central Limpopo or Greenland. These swirling structures are probably related to movements on the Cauvery dextral shear in the north and Achankovil sinistral shear in the south. The southern zone is a linear belt of khondalite-leptynite-charnockite, which is an extension of the South-West Group of Sri Lanka and Androyan Group of Malagasy. Contrary to the picture painted by Drury et al. (5), the Achankovil shear does not truncate discordant structural trends from the north. The comparison of this belt with the Eastern Ghat belt is not valid due to the absence of manganese-marble association, abundance of quartz arenites and unfavourable structural trends. The lack of worthwhile geochronological information leaves us in doubt whether this forms part of an

older gneissic terrain or a younger (Proterozoic?) mobile belt.

The contact of the Dharwar craton and this belt is a zone of transcurrent dislocation, but in point of detail this is a zone of highly ductile structures with both the terrains interacting in a diffuse mobile zone. There is no evidence in this zone for the collisional suture visualized by Drury et al. (5).

Eastern Ghat Mobile Belt: This is a long mobile belt fringing the Singhbhum and Central Indian cratons and extending to the north-east of Dharwar craton. It is predominantly composed of khondalites, charnockites, leptynites and minor amounts of manganiferous marbles and quartzites. This belt is cut off at the continental margin near Ongole, where it extends into Napier Complex of Antarctica and Highland Group of Sri Lanka. The thrust at the eastern margin of the Middle to Late Proterozoic Cuddapah basin and similar basins to the north is a late event in the polymetamorphic evolution of this belt and is not linked to the main movement of Palghat-Cauvery shear zone as suggested by Drury et al. (5). The eastern Ghat belt appears to be a product of continent-continent collision.

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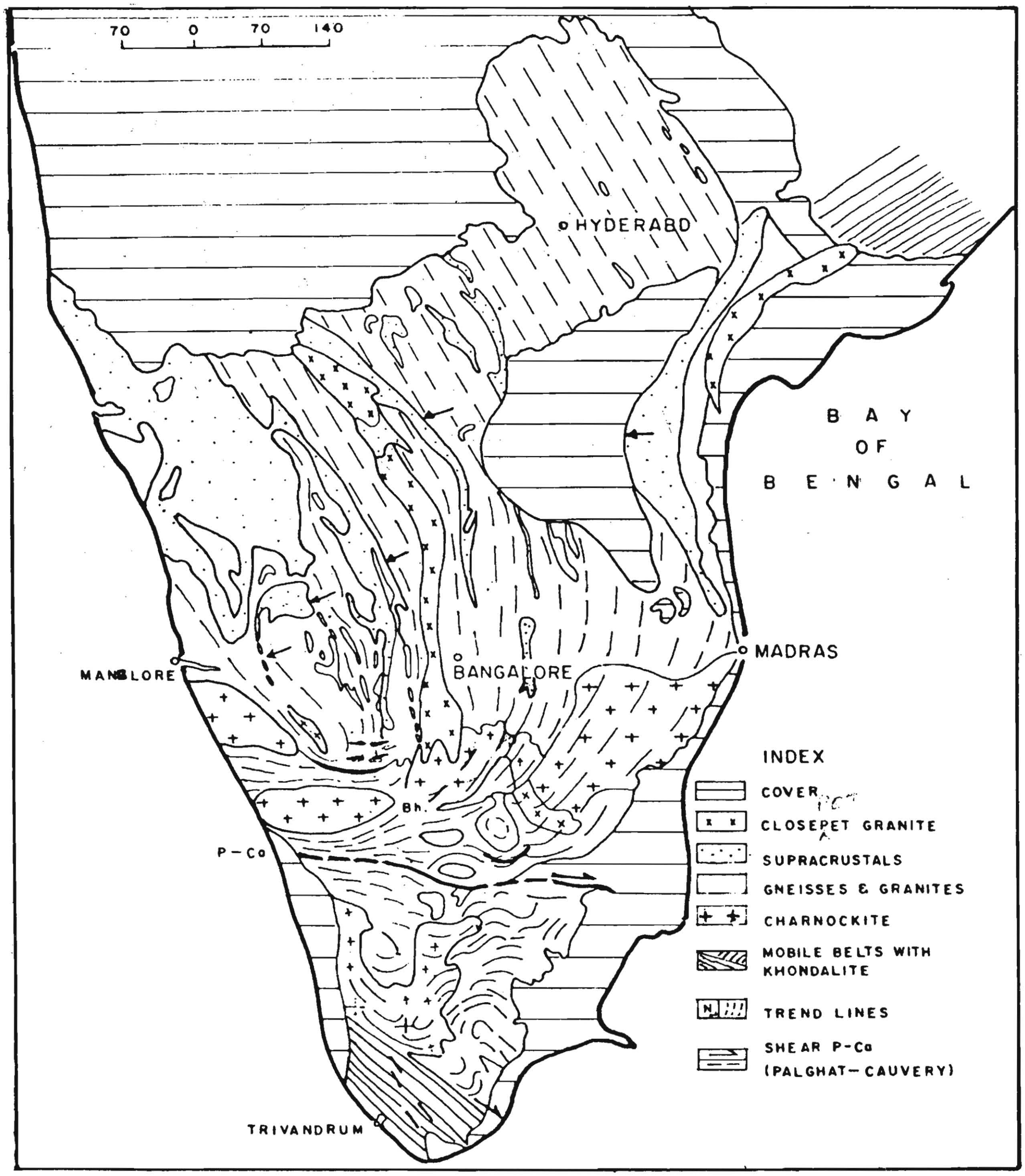
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SHEAR P-Co (PALGHAT-CAUVERY)

ORIGIN AND EVOLUTION OF GNEISS-CHARNOCKITE ROCKS OF DHARMAPURI DISTRICT, TAMIL NADU, INDIA; **D. Rameshwar Rao and B.L. Narayana,** National Geophysical Research Institute, Hyderabad, India - 500 007

A low- to high-grade transition area in Dharmapuri district has been investigated petrologically and geochemically. The investigation has confirmed the continuous section through a former lower crust, with felsic charnockites predominating the lower part and felsic gneisses the upper part.

The structure of original gneisses is preserved in charnockites and the latter show petrographic evidence for prograde metamorphism. The prograde metamorphism is of isochemical nature as revealed by the similarity of compositions of tonalitic gneisses and tonalitic charnockites. However, the depletion of LIL elements particularly Rb, caused variation in K/Rb ratios from low values (345) in the gneisses in upper part to higher values (1775) in the charnockites in the lower crust. This variation in K/Rb ratio in a north to south traverse is related to the progressive break-down of hydrous minerals under decreasing H_2O and increasing CO_2 fluid conditions. Metasomatism and partial melting has also taken place to a limited extent along shear planes and weak zones. During cooling the H_2O circulation affected substantial **auto-regression**[1] in the transition zone resulting in the formation of second generation biotite.

Geothermometry and geobarometry of orthogneisses also show a progade metamorphism from about 5-6 Kbars and $725 \pm 25^{\circ}C$ near the orthopyroxene isograd at the top of the section in the north, to about 7 to 8.5 Kbars and $775 \pm 25^{\circ}C$ towards south. The progressive increase in metamorphic grade is demonstrated by the systematic change in the mineral composition from felsic gneisses in the north to felsic charnockites in the south (eg. hornblende composition varying from hornblende-edenite to pargasite composition, and increase in contents of An in plagioclase, Ti in biotite and hornblende). The mineral chemistry in such rocks can record a depth of equilibration of minerals at 18 to 21 km and 25 to 29 km, and indicate steep geothermal gradients ranging from 35 to $38^{\circ}C/km$ and 26 to $30^{\circ}C/km$ in the upper and lower parts of the crust respectively[2]. The presence of such rocks now at the surface of the continental crust (ca. 35 km) could be cited as an evidence for this part of the Archaean crust to have been atleast 53 to 64 km thick. The differences in recorded pressure conditions might be related to the differences in erosional rates, rather than to tectonism.

ORIGIN AND EVOLUTION OF GNEISS-CHARNOCKITE ROCKS

Rameshwar Rao, D. and Narayana, B.L.

The petrochemical studies do not support the formation of the precursors (rocks of tonalitic and mafic composition) through primary fractionation of andesitic-dacitic magma[3] or intra-crustal partial melting[4]. The origin of precursors may be explained by the fractional crystallization of basaltic magma[5] or partial melting of amphibolite, leaving a mafic restite containing hornblende.

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PETROLOGY AND TECTONIC DEVELOPMENT OF SUPRA-CRUSTAL SEQUENCE OF KERALA KHONDALITE BELT, SOUTHERN INDIA.

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Granulite facies terrains are suitable models for the study of the deep crustal processess (1). The granulite terrain of southern India, of which the Kerala Khondalite belt (KKB) is a part, is unique in exposeing crustal sections with arrested charnockite growth in different stages of transformation and in varied lithological association (2). The KKB with rocks of surficial origin and incipient charnockite development, poses several problems relating to the tectonics of burial of vast area and mechanisms involved in expelling initial H_2O (causes of dryness) for granulite facies metamorphism.

The dominant lithologies in KKB are khondalite (garnet-plagioclase-K-feldspar-sillimanite-biotite-cordierite-graphite), calc-silicate, quartzite, graphite bearing garnetiferous charnockite (± cordierite), garnet-biotite gneise and leptynite (garnetiferous quartzofeldspathic gneiss). Major lithologies are interlayered both on outcrop and map scale. Arrested conversion of garnet biotite gneiss to charnockite are seen throughout the KKB. The supracrustal sequence is terminated at their northern and southern margins by garnet free massif charnockites. The few available age data ranging from 540 to 3100 Ma (3,4,5) suggest polymetamorphic history of the KKB.

The parageneses of garnet-orthopyroxene-plagioclase-biotite-quartz; garnet-orthopyroxene-spinel-cordierite-biotite-plagioclase-quartz; garnet-cordierite-sillimanite-biotite-plagioclase-K-feldspar-quartz; orthopyroxene-clinopyroxene-plagioclase; and diopside-plagioclase-calcite-scapolite-quartz document strong impressions of granulite facies metamorphism. Several progressive mineral reactions like biotite and quartz reacting to produce orthopyroxene; development of cordierite + almandine assemblages; formation of meionite replaceing calcite and plagioclase are recorded throughout the KKB. The pressure temperature conditions of metamorphism deduced from solid phase mineral chemistry indicate 4.5 to 6.5 Kbar pressure and 650 to 750°C temperature for the peak period of metamorphism (6). The P-T estimates are in consonant with the expected range from experimental phase equilibrium considerations and are fairly uniform over a large area.

PETROLOGY AND TECTONICS, S.KERALA, INDIA

Ravindra Kumar G.R. and Chacko, T.

The geochemistry of gneiss-charnockite-khondalites are comparable to arkose-pelite lithological association. The low Ni contents, lower ratios of MgO/FeO and Ni/V and typical LREE enriched nature with negative europium anamolies indicate a sialic source region. The massif charnockites, which bound the supra-crustals, have predominantly sialic composition.

It is possible to infer the following sequence of events based on the field and laboratory studies: 1) derivation of protoliths of KKB from 'granitic' uplands and deposition in fault bounded basin (cratonic rift); 2) subhorizontal deep burial of sediments; 3) intense deformation of infra and supracrustal rocks; 4) early granulite facies metamorphism predating F_2-loss of primary structure in sediments and formation of charnockites from amphibole bearing gneisses and khondalites from pelites; 5) migmatisation and deformation of metasediments and gneisses; 6) second event of charnockite formation probably aided by internal CO_2 build up(7), these charnockites are coarse, foliation blurring patches cross cutting the compositional layering; 7) isothermal uplift, entrapment of late CO_2 and mixed CO_2-H_2O fluids, formation of second generation cordierites and cordierite symplectites.

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GEOLOGY AND GEOCHEMISTRY OF THE MIDDLE PROTEROZOIC EASTERN GHAT MOBILE BELT AND ITS COMPARISON WITH THE LOWER CRUST OF THE SOUTHERN PENINSULAR SHIELD; **M.V. Subba Rao,** National Geophysical Research Institute, Hyderabad - 500 007 India

Two prominent rock suites constitute the lithology of the Eastern Ghat mobile belt : (1) the khondalite suite - the metapelites, and (2) the charnockite suite. Later intrusives include ultramafic sequences, anorthosites and granitic gneisses.

The chief structural element in the rocks of the Eastern Ghats is a planar fabric (gneissosity), defined by the alignment of platy minerals like flattened quartz, garnet, sillimanite, graphite, etc. The parallelism between the foliation and the lithological layering is related to isoclinal folding. The major structural trend (axial plane foliation trend) observed in the belt is NE-SW. Five major tectonic events have been delineated in the belt[1]. A boundary fault along the western margin of the Eastern Ghats, bordering the low grade terrain has been substantiated by recent gravity[2] and the deep seismic sounding studies[3].

Field evidence shows that the pyroxene granulites (basic granulites) post-date the khondalite suite, but are older than the charnockites as well as the granitic gneisses[4]. Polyphase metamorphism, probably correlatable with different periods of deformation is recorded.

Using geochemical parameters, it is inferred that the basic granulites could be an earlier phase of the charnockite suite and genetically related to the charnockites. The relationships of relatively immobile elements like Mg-Zr, Ca-Y, Zr-Y and the rare earth element (REE) patterns suggest that the protoliths of these rocks are derived from a single source. The REE data supports the field relations that the basic granulites are emplaced earlier compared to charnockites and the source material for these rocks could be a metasomatised mantle, enriched in LREE.

K-Rb relations suggest that these elements have been depleted in all the litho-units during the granulite facies metamorphism; however, restoration of some of these depleted elements to varying degrees by metasomatic enrichment has been observed. This restoration may be the result of the Eastern Ghat orogeny.

The granulites of the mobile belt as a whole are characterised by variable LIL element geochemistry, while the cratonic granulites show a lesser degree of variation. This could be attributed to the deformation and the orogenic effects in the mobile belt. The variation in lithology suggests that, while the lithologies of the Eastern Ghat belt evolved in a geosynclinal type environment, the cratonic granulites could be the deeply eroded sections of the crust or the high-grade equivalents of the amphibolite grade terrain to the north of this section, which have not witnessed much of tectonic deformation and the attendant chemical changes.

The cratonic granulites are Na-rich, whereas the granulites of the Eastern Ghats are in general K-rich; the latter are also enriched in Rb, Ba and Th. The immobile element concentrations like Zr, Y and REE which indicate the origin of the protolith, are more in the Eastern Ghat mobile belt granulites, compared to the cratonic granulites. Total REE levels as also LREE enrichment are more in the Eastern Ghats granulites. An inhomogeneous amphibolite source of variable mineral or chemical composition has been postulated for the charnockites of the craton[5]. The charnockites of the Eastern Ghats based on their immobile element geochemistry appear to have been derived from a homogeneous source.

The field relations in the Eastern Ghats point to the intense deformation of the terrain, apparently both before, during and after metamorphism. This, coupled with close intermingling of granulites and the khondalite suite and a greater abundance of khondalites[6] indicate that the Eastern Ghats granulites were developed during an intense deformation (perhaps collisional) event, whereas no such evidence has yet been found in the southern granulite terrain.

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ELECTRICAL STRUCTURE AND ITS IMPLICATION ACROSS THE LOWER- AND UPPER-CRUSTAL SETTINGS OF SOUTH INDIA, **U.Raval, National Geophysical Research Institute, Hyderabad-500007, India.**

Measurements of a large scale MMA experiment covering both the granulite and greenstone terrains of Archeans in the southern part of India is re-visited and re-analysed. The induced field variations contain the signatures of crustal and subcrustal electrical conductivities, although substantially distorted by the sea-land interfaces and cenozoic sediments. However, through a selection of some reconnaissance profiles and temporal variations, an attempt is made to deduce whether (i) significant differences exist between the electrical structures of the high and low grade complexes i.e. if the electrical conductivity of the lower crust is due to minerological composition or is intrinsic to the positioning at depths (> 15 km), (ii) the probable seaward extension of the continental crust and its transition to oceanic type may also contribute (through intracrustal DC-like telluric sheets) to the induction field in addition to or rather than the sharply localized zones, (iii) the observed parameters are indicative of a formal anisotropy and/or undulations in the deep crust, and (iv) the postulate of relatively hotter Indian shield is reflected particularly with regard to differential metamorphism. In the last case, the crust-mantle coupling in this region - unlike other similar areas - seems to be markedly affected by the evolution of NE-plate velocity field.

Thus the possible heating due to shear at the litho-asthenosphere boundary and difference in the rheological response of the two types of crustal zones provide some clues for the observed uplifts, unloading and other tectonic elements. For example, the Palghat gap may be due to thermomechanical adjustments in response to the secular changes in the regional stress regimes. The response modification noticed at some central stations which lie near the vicinity of the transition may be due to intracrustal overlapping implying presence of fluid at possible dipping contacts or to non-uniform metamorphism. Some model results are also presented to emphasise (a) above points in conjunction with available geophysical information and (b) MT coverage of this window to the lower-crust and underlying mantle.

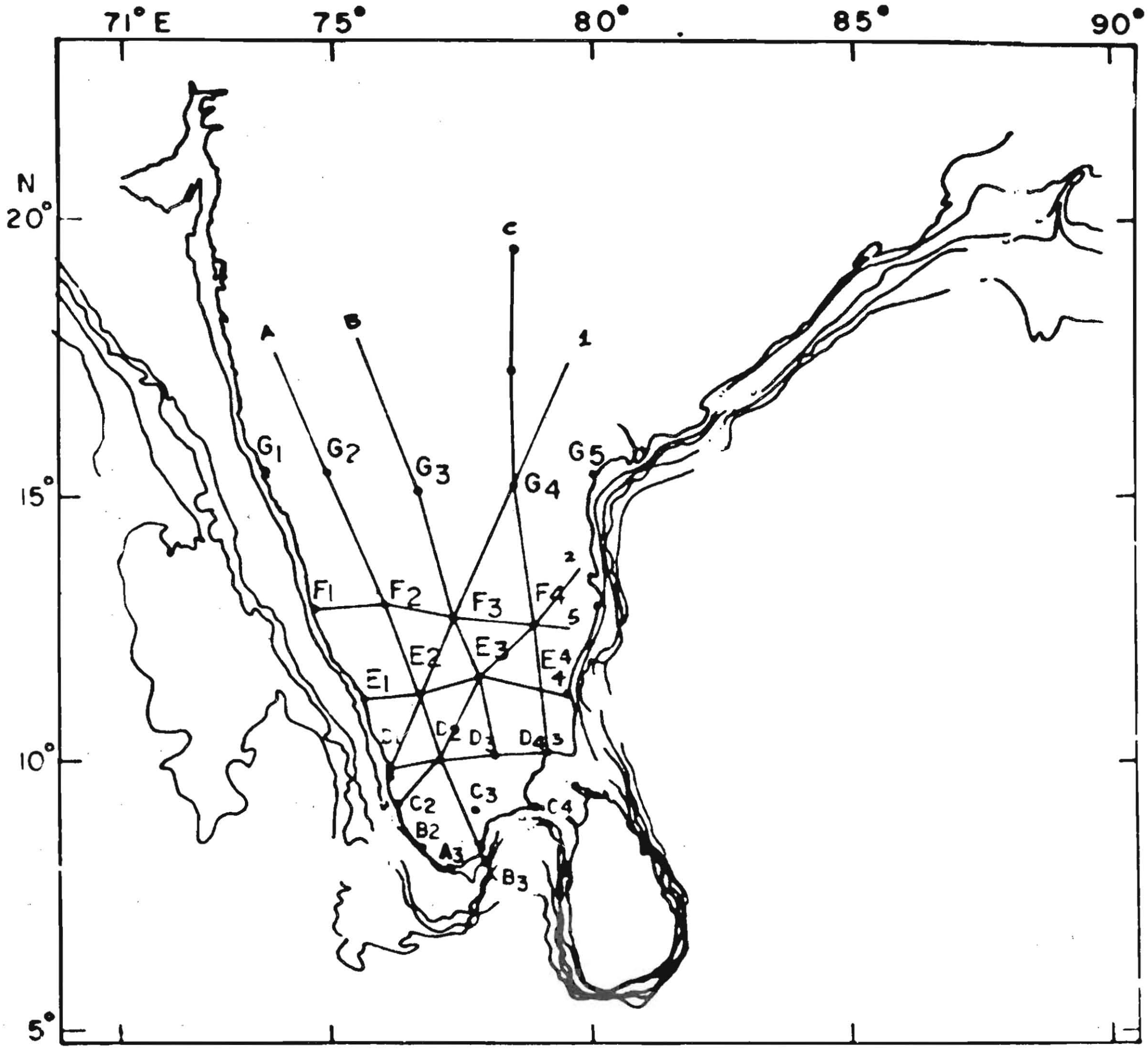

Fig.1. MMA stations of the GDS experiment and selected reconnaissance profile over the greenstone-granulite terrains.

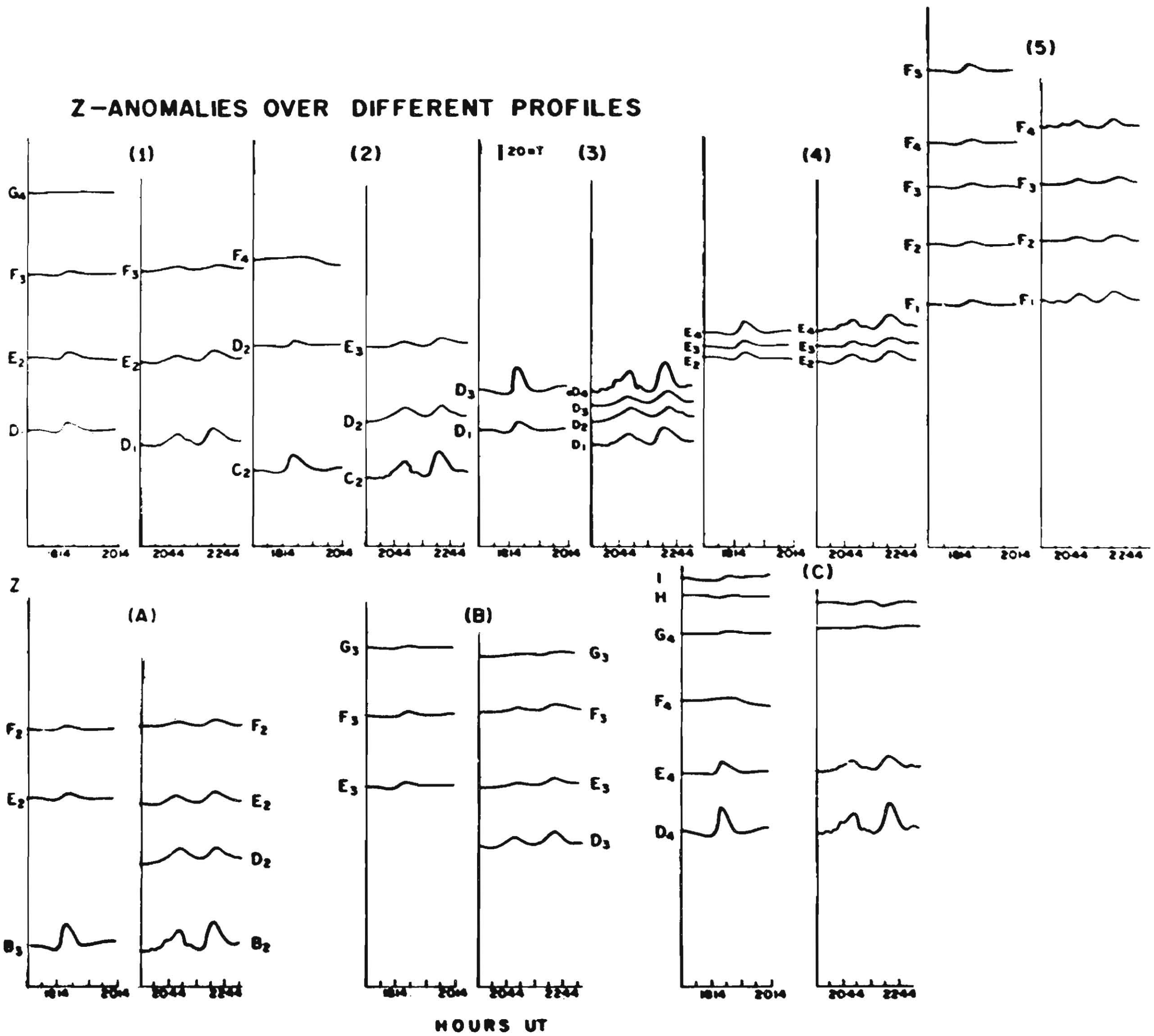

Fig.2. Z-response over the selected profiles (Fig.1).

PAN-AFRICAN ALKALI GRANITES AND SYENITES OF KERALA AS IMPRINTS OF TAPHROGENIC MAGMATISM IN THE SOUTH INDIAN SHIELD

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Granite and syenite plutons with alkaline affinities ranging in age from 550 to 750 Ma sporadically puncture the Precambrian granulites of the Kerala region. All the bodies are small (20-60 sq km), E-W to NW-SE elongated elliptical intrusives with sharp contacts and lie on or close to major late Proterozoic lineaments.

Mineralogically, perthitic K-feldspar is the dominant constituent of all the plutons. The modal Q-A-P contents mainly fall in the quartz-alkali feldspar syenite, quartz-alkali feldspar granite and granite fields. Greenish hornblende is the dominant ferromagnesian phase, with subordinate amounts of biotite. Minerals typical of alkaline plutons such as riebeckite, aegirine and acmite occur in some of the plutons. Melanite garnet, monazite, zircon, apatite, calcite, epidote and phlogopite are accessories.

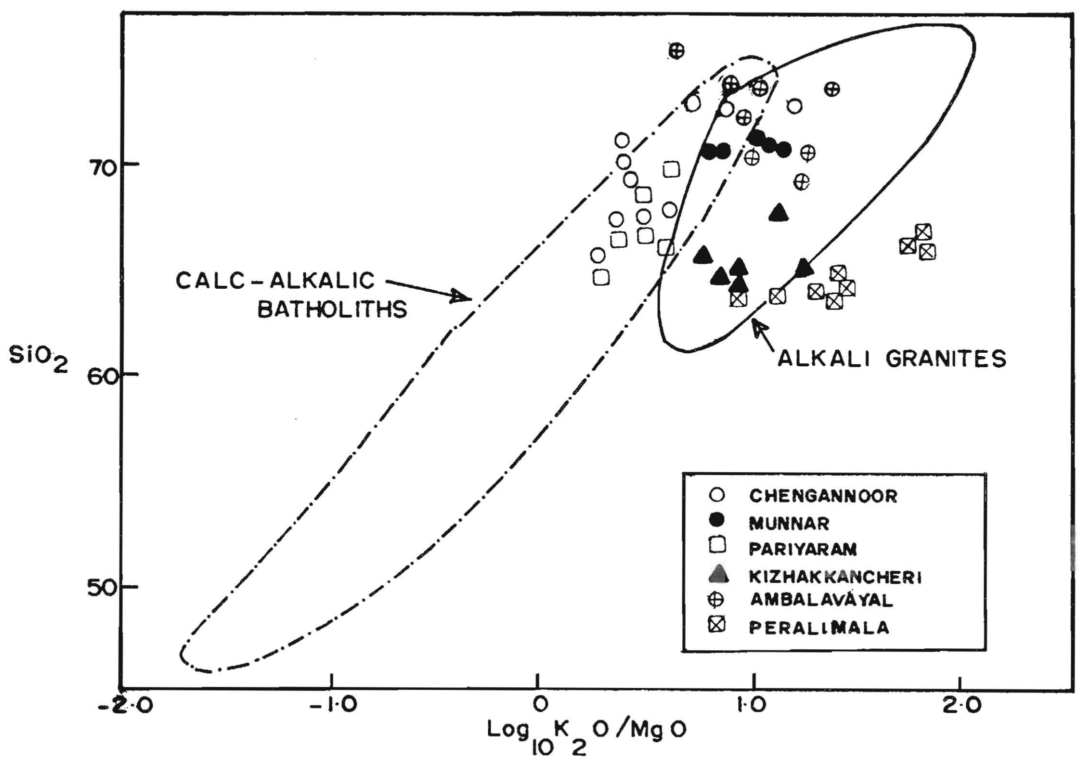

Fig.1 SiO_2 Vs. Log_{10} K_2O/MgO plots of the Kerala granites (1)

Geochemical plots of A-F-M and An-Ab-Or relations show an apparent alkali enrichment trend on the former, but the plutons define relatively distinct fields on the latter. Most of the plutons are adamellitic to granitic by chemistry. The variations of SiO2 with $\log_{10}$ K_2O/MgO (1) brings out the distinct alkaline nature of the plutons (Fig. 1). Some of the granites are extremely potassic, like the Peralimala pluton, which shows upto 11.8% K_2O. On a SiO_2 - Al_2O_3-Na_2O+K_2O (mol %) plot, the plutons vary from peraluminous to peralkaline, but none are nepheline normative. Low MgO, low to moderate CaO and high Fe_2O_3/FeO values are other common characteristics. Among trace elements, depletion of Ba, Sr and Rb with high K/Ba and K/Rb values are typical. Overall, the plutons show a trend of decreasing K/Rb ratio with increasing K content. Individual plutons show more clearly defined trends similar to those from granitic masses characterised by plagioclase fractionation. Many individual samples show greater Rb depletion relative to K than normal alkali granites.

In their analysis of means of discriminating granites from a variety of tectonic settings, Pearce et al (2) found the most useful elements to be Rb, Ta, Nb, Y and Yb. Plots of the Kerala plutons based on these parameters (eg. shown in Fig. 2) fall mainly in the volcanic are granite field, close to the WPG-COLG-VAG triple point, except the Ambalavayal pluton which falls well in the within-plate field.

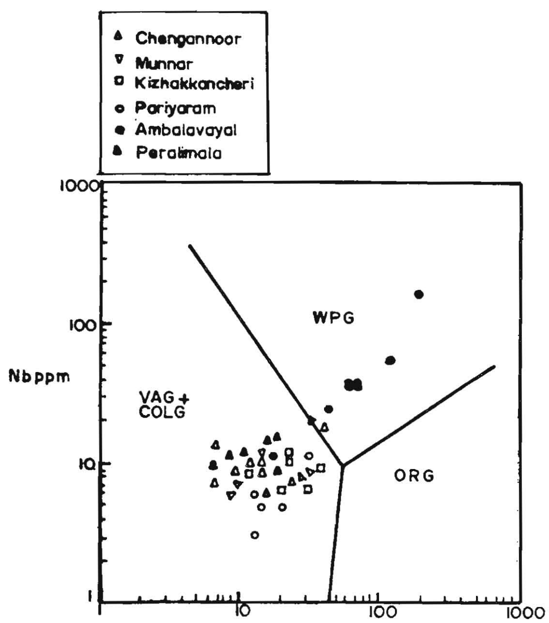

Fig.2 Nb Vs. Y plots of the Kerala plutons.

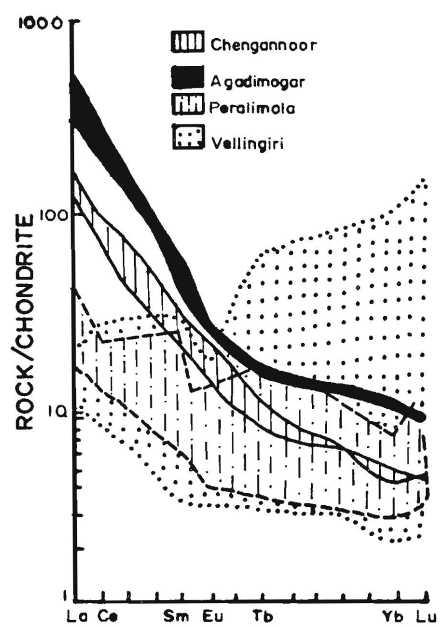

Fig.3 Chondrite normalised REE patterns of the Kerala plutons.

The total rare earth element (REE) contents in these plutons widely vary (32.4 to 425ppm) but show a close relationship with the agpaitic indices, the more alkalic plutons having low total REE levels. The chondrite normalised REE patterns (Fig.3) exhibit steep LREE to HREE slopes for some plutons whereas a few show HREE enrichment, attributed to variations in source compositions and/or subsequent fractionation history. Based on geochemical characteristics, the plutons could be regarded as two distinct groups. Those with lower K_2O, K_2O/Na_2O and K_2O/MgO as well as low agpaitic indices have high total REE levels, LREE/HREE ratios and (Ce/Yb)n values. These plutons exhibit steep LREE to HREE gradients and have no Eu anomaly. They also show low U and high Th values. The other group has markedly high K_2O, K_2O/Na_2O, K_2O/MgO and relatively higher agpaitic indices. These plutons show low total REE, LREE/HREE ratio, (Ce/Yb)n levels and consistently low U and Th values.

Petrogenetic considerations show that among the various models proposed for the origin of alkaline silicic plutons, decompression melting caused by crustal distension (3) is the most viable mechanism which could explain the generation of alkaline magmas in stable plate interiors as in the present case. The low initial Sr-isotope levels (0.7031-0.7032) for these plutons and the consistently high K/Rb values are consonant with this model and indicate a K-enriched Rb-depleted deep crustal or upper mantle source. Peralkaline plutonism is an essential part of pre-rift tectonics and is especially important in the early stages of tensional tectonics. Abnormal enrichment of alkalies is viewed to be the key-note of rift mechanism. Since the plutons are spatially related to regional fault-lineaments, some of which are taphrogenic in nature, it is envisaged that this alkaline magmatic regime is a probable manifestation of the pre-rift tectonics related to the taphrogenesis of the Indian continent and the supercontinent of which it was a part during the Pan-African.

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CHARACTERISTICS AND CARBON STABLE ISOTOPES OF FLUIDS IN THE SOUTHERN KERALA GRANULITES AND THEIR BEARING ON THE SOURCE OF CO_2

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Carbon dioxide-rich inclusions commonly occur in the banded charnockites and khondalites of southern Kerala as well as in the incipient charnockites formed by desiccation of gneisses along oriented zones. Comprehensive micro-thermometric measurements constrain their densities to be in the range of 0.95-1.0 g/cm^3 in banded charnockites, 0.87-0.97 g/cm^3 in khondalites and 0.83-0.95 g/cm^3 in incipient charnockites. The combined high density fluid inclusion isochores and the range of thermometric estimates from mineral assemblages (Fig. 1) indicate entrapment pressures in the range of 5.4 to 6.1 Kbar. The CO_2 equation of state barometry closely compares with the 5 $\pm$ 1 Kbar estimate from mineral phases for the region (1,2,3). The isochores for the high density fluid inclusions in all the three rock types pass through the P-T domain recorded by phase equilibria, implying that carbon dioxide was the dominating ambient fluid species during peak metamorphic conditions.

In order to constrain the source of fluids and to evaluate the mechanism of desiccation, we have taken up detailed investigations of the carbon stable isotope composition of entrapped fluids. We report here the results of our preliminary studies in some of the classic localities in southern Kerala namely,

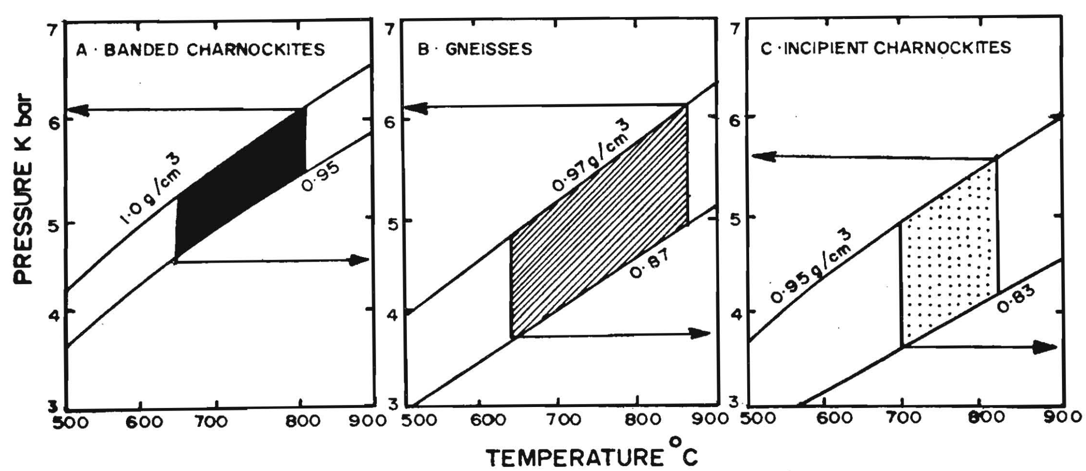

Fig.1 Combined P-T data from mineral thermometers and fluid inclusion isochores for the Kerala granulites. The shaded regions represent the P-T domains, with arrows denoting the highest and lowest pressure estimates.

Ponmudi, Kottavattom, Manali and Kadakamon. In Ponmudi and Kottavattom, garnet-biotite gneisses transform into patchy charnockites and the arrested prograde reaction is manifestly that of biotite+garnet+quartz to orthopyroxene +K-feldspar+ilmenite (4). In the Manali quarry, east of Trivandrum, interbanded and co-folded banded charnockites and garnet-biotite$\pm$cordierite gneisses are cut by later incipient charnockites developed along oriented zones. Two of our samples come from Kadakamon area where calc-silicates are interlayered with cordierite-bearing banded charnockites.

A stepped heating technique was adopted whereby quartz samples from the granulites were heated in 100^{o}C steps from 300 to 1200 degrees and the abundance and isotopic composition of the carbon dioxide evolved at each step was measured on an ultrasensitive mass spectrometer. The stepped release profiles of all the samples are broadly similar (eg. shown in Fig. 2) and show a maximum carbon release between 600 and 800^{o} . This release is interpreted as carbon dioxide from decrepitation of fluid inclusions and is characterised by the isotopically heaviest carbon in the samples. This has been systematically checked by visual decrepitation of fluid inclusions in doubly polished plates of the same samples, by heating the inclusions in a Leitz-1350 heating stage, when the carbonic inclusions recorded maximum explosions between 500 and 800^{o}C.

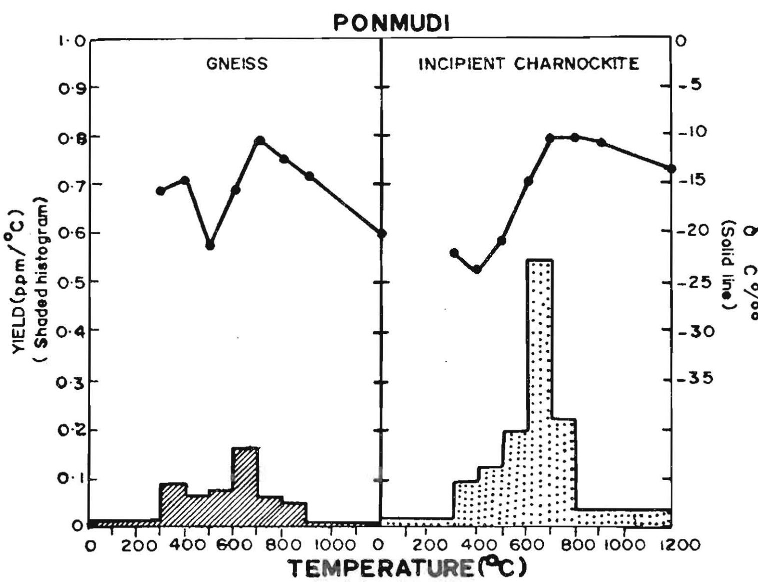

Fig. 2 Stepped-release profiles for gneiss-incipient charnockite pairs. The histograms represent carbon dioxide abundance and the thick lines join the stable carbon isotopic composition at each step.

The analytical results show that the banded charnockites and gneisses contain about 50-60ppm carbon, whereas the incipient charnockites are characterised by more abundant (100-200ppm) carbon. The carbon isotopic compositions range from -10‰ to -12‰ in banded charnockites and -8% to -10.3‰ in the gneisses. The incipient charnockites show d13C values between -7.5 and -10.3‰. The calc-silicate yielded a d13C value of +1.2‰. Carbon dioxide generated by decarbonation reactions would be enriched in lighter carbon isotopes as compared to the carbonate. The contrasting values of +1.2‰ for the Kadakamon calcsilicate and -10‰ for the interlayeredbanded charnockite preclude an origin by decarbonation. The -7.5‰ d13C value for the incipient charnockite of Manali shows marked enrichment in heavier carbon as compared to the associated banded charnockites (-12.3‰) and gneisses (-11‰), suggesting a juvenile source. The isotope values for the main release peak, when plotted against carbon abundance show no pronounced correlation between gneiss-incipient charnockite pairs, suggesting that simple fluid flushing did not occur. Moreover, at Ponmudi and Kottavattom, the d13C values of incipient charnockites are isotopically lighter and with essentially no pronounced difference from the d13C values of the precursor gneisses. Isotopic exchange between an externally derived fluid and graphite in the rock would considerably enrich the carbon dioxide with lighter carbon. We hence interpret the lighter d13C values in these samples to be the result of the interaction of externally derived fluids with graphite that is ubiquitously present in the precursor gneisses and incipient charnockites in these localities.

Eventhough the apparent small shift in carbon isotope composition during charnockite formation is consistent with internal buffering, the observed carbon dioxide abundance in the incipient charnockites as compared to their precursor gneisses argues for external buffering of CO_2. This leads us to infer that eventhough some fluid flushing did occur, it equilibrated with graphite present in the rocks during charnockite formation.

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GRANULITES FROM NORTHWEST INDIAN SHIELD : THEIR DIFFERENCES AND SIMILARITIES WITH SOUTHERN INDIAN GRANULITE TERRAIN. R.S.Sharma, Department of Geology, Banaras Hindu University, Varanasi-221005, India

Granulite facies suite in NW Indian Shield is exposed at Sand Mata, Udaipur district, Rajasthan, as an oval-shaped massif within amphibolite facies rocks of the Banded Gneissic Complex (3.5 to 2.6 b.y. old) — a possible analogue of the Peninsular gneiss of Dharwar craton. The contact of the granulites with the surrounding gneisses is demarcated by a shear zone of 10 to 15 m width with a steep down dip lineation. The granulites have a general strike of N-S to NNW-SSE, with gentle to high dips towards east, and record three fold phases. The first (F_1) is seen as rootless folds with W to SW trending axial planes. The second folds (F_2) are isoclinal or reclined with NW-SE to N-S trending axial planes. The third phase (F_3) is characterized by vertical to very steep fold axes, producing vortex or 'Schlingen' structure.

The granulite suite of Sand Mata consists three main rock types. Amongst them the pelitic granulite dominates and contains garnet, biotite, sillimanite, kyanite, quartz, feldspar and occasionally cordierite. Within this granulite gneiss occur discrete bands of charnockite and enderbite along the strike of the gneiss from which they seem to have derived. Interlayered with the pelitic granulite is another lithotype, the garnet leptynite containing garnet-quartz-feldspar, which at places shows gneissic fabric. The pelitic granulite-leptynite association is traversed along and across the banding by smoky and blue quartz veins and by pegmatites of at least three generations, sometimes with garnet. At the structural base of the banded granulite is the third rock-type, the garnet-bearing basic granulite which together with the other two lithologies build the well-known granulite complex of Sand Mata. The complex is intruded by norite dykes of uncertain age, with crystallization temperature of about 1150°C.[1]

Mineralogical studies show that in the basic granulite the orthopyroxene-plagioclase pair is incompatible and is separated by corona of garnet-clinopyroxene-quartz, suggesting it to be a high pressure granulite.[2] Random orientation of the corona minerals suggests that the granulite facies metamorphism occurred in a deformation-free environment, akin to charnockite forming conditions in the southern Indian Shield. The pelitic granulite is characterized by overprinting of kyanite by sillimanite which, in turn, is followed by growth of second generation kyanite, mostly in the form of needles. These assemblages are thus consistent with the polymetamorphic character which is also found in schists of the gneissic complex from north-central Rajasthan.[3] The norite dyke shows blastophitic texture as well as metamorphic growth of garnet at the interface of plagioclase and hypersthene, suggesting that the dyke was emplaced during waning stages of granulite facies metamorphism. The mineralogy of the norite dyke further suggests that the corona texture in the garnet-bearing basic granulite has not formed during cooling.

Estimates of temperature conditions by different geothermometers give values which cluster about 850°C and 650°C for the basic assemblages and 650° ± 50°C for the pelitic assemblages. These two concentrations of temperature values (850° and 650°) possibly are suggestive of climactic and blocking temperatures respectively during the granulite facies metamorphism. Application of different geobarometers to the investigated assemblages yields pressures in the vicinity of 5 ± 1 kb and 10 ± 2 kb. Interestingly, the pressure estimate for the garnet-core composition is lower than that for the garnet-rim composition by the same equilibria involving cordierite in the pelitic composition. Higher pressure values for the rim than for the 'core' composition of garnet are also found in the anhydrous garnet-plagioclase-Al_2SiO_5-quartz equilibria. This feature suggests that there was loading during cooling of the Sand Mata rocks. The concentration of P values at about 8-11 kb and near 5 kb, with almost no record of intermediate values perhaps indicates that the rocks were suddenly transported from deeper levels and emplaced to shallower depths (ca. 5 kb) where frozen-in equilibrium was attained in the assemblages. This is evidenced by the occurrence of the peripheral shear zone. This situation is in marked contrast with the granulitic rocks of southern Indian Shield. Also, there is no transitional facies rocks in the Sand Mata area, unlike that in the Dharwar craton.

On the basis of quantitative P-T estimates, combined with the textural evidence for the crystallization sequence of the Al-silicate polymorphs (kyanite → sillimanite → kyanite) in the pelitic granulite, the deduced P-T path for the Sand Mata granulites is the reverse of that characterizing the Plate tectonic collision zone. It however agrees with the P-T path inferred in the case of the southern Indian granulitic rocks.[4]

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THE ROLE OF BORON AND FLUIDS IN HIGH TEMPERATURE, SHALLOW LEVEL METAMORPHISM OF THE CHUGACH METAMORPHIC COMPLEX, ALASKA

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The possible role of boron (B) involvement in granite equilibria and generation of melts during crustal metamorphism has been a focus of speculation in recent literature (1,2,3). Most of the evidence for such involvement derives from experimental data which implies that the addition of B will lower the temperature of the granite solidus (4,5). Also the presence of tourmaline has a minor effect on the temperature of the solidus (6). Further indirect evidence that B may be involved in partial melting processes is the observation that granulites are commonly depleted in B (7), whereas the B content of low grade metapelites can be high (up to 2000 ppm, 8 & 9). Our measurements of the whole-rock B contents of granulites from the Madras region, India are low, ranging from 0.4 to 2.6 ppm, and Ahmad and Wilson (10) suggest that B was mobilized in the fluid phase during granulite facies metamorphism of the Broken Hill Complex, Australia. Thus, it appears that during the amphibolite to granulite transition, B is systematically lost from metasediments. The B that is released will probably partition into the vapor phase and/or melt phase.

Field data from a high temperature, shallow level regional metamorphic complex in the eastern Chugach Mountains of southern Alaska indicate localized partial melting has occurred in response to increased heat flux from intrusion of tonalite sills and plutons (11). In addition, the amount of tourmaline increased with increased metamorphic grade. However, in the migmatitic core of the complex, tourmaline is absent in the partial melt zones and rare in the host metasediment. The conditions of metamorphism (400 ^{o} to 600 ^{o}C outside the migmatitic core and 650 ^{o}C within the core at pressures of 2.5 to 3.5 kbar). and the presence of locally derived granitic melts, imply that B may be involved in the partial melting process. Approximately 3 wt % B_2O_3 is needed to lower the granite solidus from 700 ^{o}C to 650 ^{o}C (5). The breakdown of tourmaline may release the B necessary for fluxing the partial melting. The boron-rich fluid or melt is inferred to have escaped and is possibly represented by late stage tourmaline-bearing pegmatites and tourmaline-quartz veins. Below we present our preliminary results from whole-rock boron analysis and fluid inclusion observations done to explore the role of boron and fluids during the migmatization of the Chugach region.

The Chugach Metamorphic Complex (12,13,14) is developed in the Campanian to Maastrichtian Valdez Group, which is predominantly clastic argillite and graywacke with minor tuffaceous basalt deposited in either a trench setting or a deep sea fan. The entire region was metamorphosed to greenschist facies at 55-60 Ma, possibly by a combination of heat conduction from subducted hot, young oceanic crust (15) and heat advection from dewatering of fluids from sediments at depth in a subduction zone setting (16). The whole-rock boron content of the greenschist package is moderate and the concentration of the B is controlled by the host lithology (Table 1). The fluids involved in greenschist metamorphism are represented by hot, low salinity brines observed in fluid inclusions in first generation quartz veins. Later brines have both lower salinities and homogenization temperatures which may reflect cooling of the fluid and possibly mixing with meteoric fluids. The salinity decrease is correlated with a decrease in B content (Table 1). A similar relationship between B and Cl^- (salinity) has been observed in thermal waters (e.g. Yellowstone, 17).

The regional high temperature metamorphism followed the greenschist event in response to intrusion of tonalite sills and plutons at 55 Ma. Initial measurements of the Chugach whole-rock boron content of samples from the amphibolite facies and migmatitic core are low suggesting B has been lost. This may be related to the breakdown of tourmaline. However, some of the highest grade samples still have B contents similar to the greenschists (compare sample 96 with 7, Table 1). Additionally the B content of the intrusive tonalites (samples 11 and 103, Table 1) and the locally derived granitic melts (sample 98A1, Table 1) is low. The low boron in all these rock types and lack of tourmaline in the intrusive tonalites suggests that B is not present in sufficient quantity to have any affect on the solidus of the melts. However, some of the boron originally in the melt phase may have preferentially partitioned into a vapor phase leaving the tonalites and locally derived granites with low B content.

The majority of the fluid preserved as fluid inclusions in the Chugach Metamorphic Compex is CO_2-rich and the primary fluids have isochores which pass through peak metamorphic conditions. The B content of the host quartz veins is low (Table 1). One vein in the amphibolite facies region does preserve a transition from H_2O-CO_2 mixture to pure CO_2. The salinity of the H_2O component is not great enough to suggest fluid immiscibliity as a cause for the composition change at these metamorphic conditions (550 ^oC and 3 kbar). However, a possible explanation for the composition change is that the water has been incorporated into either the intrusive tonalites or locally derived melts. Thus, the CO_2 may represent a residual fluid. Olsen (18) describes a similar relationship for CO_2-rich fluids preserved in migmatites from Colorado.

These preliminary measurements imply that the boron content of rocks in the Chugach Metamorphic Complex is not sufficient to influence the processes of partial melting at low pressures. Further work is needed to constrain the mass balance of B during progressive metamorphism and evaluate the possiblity that both B and H_2O have been incorporated into melts which have since left the system.

TABLE 1. BORON CONTENT OF CHUGACH METAMORPHIC COMPLEX

Sample	Rock Type	Temperature (^oC)*	Boron (in ppm)**
6	graywacke	400	46
10	graywacke	400	39
45B	graywacke	400	48
48B	graywacke	400	23
50B	graywacke	400	37
7	argillite	400	29
45A	argillite	400	18
48A	argillite	400	25
50A	argillite	400	18
8B	basalt	400	4.6
48D	basalt	400	2.7
64A	qtz vein	450, 3.5 wt %	2.6
64C	qtz vein	375, 2 wt %	0.7
64D	qtz vein	250, 0.5 wt %	0.4
8BV	qtz vein	375, 3.5 wt %	0.2
10BV	qtz vein	400, minor CO_2	0.9
89D	qtz vein	600, CO_2-rich	2.1
93R	qtz vein	550, CO_2-rich	2.3
12	schist	500	2.7
17G	schist	500	50
35	schist	575	8.5
45	schist	540	2.3
94L	schist	550	42
31D	schist	600	6.6
86E	schist	600	18
110	migmatite	650	6.7
96C	migmatite	650	46
98A2	migmatite	650	8.2
98A1	granite melt	--	7.6
103	tonalite	--	6.7
108	tonalite	--	2.3
11	tonalite	--	3.0
105	tourmaline-selvage	--	210

Table 1 (cont'd)

* Temperature is either estimated from mineral assemblage data or for quartz veins is derived from the fluid inclusion isochore and the composition is given with salinity in wt % NaCl equivalent.
** Boron measured by prompt gamma neutron activation analysis (PGNNA) at the McMaster University reactor centre. Precision is approximately 10% for concentrations above 10 ppm and falls to 30%-50% near the detection limits (< 0.5 ppm).

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GEOCHEMISTRY AND ORIGIN OF GOLD MINERALIZATION IN THE KOLAR SCHIST BELT

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The Kolar Schist Belt is the most important gold producing, volcanic-dominated, Archean belt of the Dharwar Craton. Gold occurs here as gold-quartz-sulfide lodes and as gold-quartz-calcite veins, the latter confined only to the eastern part of the belt. Profuse mineralization and extensive mining have been confined to the central part of the belt, Kolar Gold Fields (KGF). Recently, economic concentrations of gold mineralization has been discovered in the southern part of the belt, whereas in the northern part mineralization is reported to be poor and uneconomic.

The gold-quartz-sulfide lodes occur either associated with thin units of banded iron formation interbanded with komatiitic and tholeiitic amphibolites or directly with the latter. There are several parallel lodes in the KGF area. The lodes occur all along the strike, from central to southern parts of the belt discontinuously. The lodes in general are typically banded/layered, are parallel to the schistosity of the amphibolitic host rocks and appear to have been confined to the contacts of different textural varieties of amphibolites. Wall-rock alteration, characterized by the presence of biotite and/or garnet is restricted to a few centimeters on either side of the lodes. In KGF, the sulfide lodes are interbanded with graphitic schists. Graphitic schists are not encountered in the southern part.

Sulfide lodes consist of bands/layers of cherty-quartz, sulfides and mafic silicates. In KGF, the lodes also include magnetite bands. Here the width of the bands decreases towards western margin of the belt. Bands/layers are at places deformed because of complex folding and shearing. The sulfide mineralogy includes dominantly pyrrhotite and arsenopyrite. Minor sulfide phases include loellingite, chalcopyrite, sphalerite and pyrite. Pyrrhotite and arsenopyrite tend to occur as monomineralic layers. Pyrrhotite is present essentially as hexagonal type. Arsenopyrite occurs as coarse to medium grained euhedral crystals which are often deformed. Gold commonly occurs as patchy inclusions within the deformed arsenopyrite crystals and as sub-rounded inclusions within the silicates. In KGF, the sulfide lodes include magnetite, ilmenite and graphite. Although the major sulfide mineralogy is remarkably uniform among the various lodes in the belt, the total sulfide and arsenopyrite contents of the lode matter are quite variable. However, there is no correlation among the total sulfide contents, (5-35 volume per cent) concentration of base metals and that of gold. Base metal concentrations are significantly low except in the westernmost and southernmost lodes. The gold concentration varies between 1 to 6 ppm and does not correlate with arsenopyrite contents of the lodes. However, in the KGF area, among the four sulfide lodes there is a definite mineralogical and geochemical zoning. Base metals, total sulfide, K_2O, Al_2O_3 and graphite increase from east to west; arsenopyrite, magnetite, iron and gold decrease from east to west. The sulfide mineral assemblage represents a minimum temperature of equilibration $\sim 500^{\circ}C$.

GOLD MINERALIZATION

Siva Siddaiah N and Rajamani V

Gold-quartz-calcite lodes, occur exclusively on the eastern side of the belt, close to the felsic schists and gneisses known as the Champion Gneiss. Although the lodes are parallel to the general strike of the belt, at many places they make a small angle with the schistosity of the amphibolitic host rock. The lodes appear to be fracture-filled veins within the country rock with a narrow zone of calcite-biotite alteration. The lodes at many places are also sheared. They consist dominantly of quartz, calcite, albite $\pm$ biotite $\pm$ sulfide and tourmaline. Sulfide content is usually very small, much less than a per cent. Galena is reported to be the dominant sulfide (1). The average concentration of gold is 10 ppm occurring essentially as native gold. Base metals are present in very low concentration. However, Cr and Ni show much higher abundances, as much as 400-500 ppm for lodes rich in quartz and calcite. The lodes have remarkable depth persistence ($>$ 3.5 km) and there are no observable changes in the gold tenor, nor in the nature of alteration with depth. Fluid inclusion and oxygen isotope data, suggest that the temperature of precipitation was around 300^{o}C and it occurred from a uniform reservoir of fluid at least for 3 km depth (2, 3, 4). Alteration and mineralization in the quartz lodes appear cogenetic and postdate peak metamorphism.

Geological, mineralogical, mineral-textural and geochemical data of the sulfide lodes in the belt indicate that the gold mineralization could be related to low temperature, low Eh and high pH rock-dominated geothermal systems set up in the submarine volcanic pile prior to amphibolite metamorphism. Relatively long-lived geothermal system produced an economic deposit, whereas short-lived ones, because of rapid burial by younger basalts throttled the geothermal system and diffused the discharge yielding low grade ore bodies. The source for gold and iron could be iron enriched tholeiites derived from source regions enriched in komatiitic melt components (5) and komatiitic rocks derived by very low extents of melting of metasomatised mantle sources (6). On the other hand, the geographical restriction of the quartz-calcite lodes, their mineralogical and geochemical data and their estimated temperature of formation all seem to suggest that a major part of the hydrothermal fluids, and a significant portion of gold could have been derived from mantle derived intrusive, sanukitoid type magma sources, similar to the Champion Gneiss occurring on the eastern part of the belt (7). However, the possibility of some input by remobilization of a premetamorphic sulfide protore to quartz lodes cannot be ruled out completely.

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RETROGRADE,CHARNOCKITE- GNEISS RELATIONS IN SOUTHERN INDIA; C.Srikantappa, K.G.Ashamanjari, K.N.Prakash Narasimha, Department of Geology, University of Mysore, Manasagangotri, Mysore 570 006, India; and M.Raith, Mineralogisch-Petrologishes Institut, Universitat Bonn, Poppelsdorfer Schloss, 5300 Bonn, West Germany.

The Nilgiri charnockite massif (Δ 2694 m above MSL) in southern India is bordered by two major shear belts viz. Moyar and Bhavani, formed probably during late Proterozoic times. The Moyar shear belt separates the predominantly amphibolite facies gneissic terrane (Dharwar Craton, 3.4 b.y. old,[1]) in the south. This shear belt is upto 20 km. wide and 200 km. in length. LANDSAT imagery studies coupled with field observations indicate the development of a major N 30°W trending lineament cutting the earlier N 70-80°E to E-W trending shear fabric. The structures within the Bhavani shear belt which forms the southern boundary of the Nilgiri charnockite massif is N 60-70°E trending, essentially parallel to the structures of the Nilgiris. These shears are cut by late N-S to N20°W shear planes. Southern boundary of the Bhavani shear belt joins with the wide plains of Noyal-Cauvery shear belt.

The high-pressure charnockites (P = 8-9 Kb., T = 700-800°C CO_2-rich fluid regime) of the Nilgiri hills show evidence of retrogression related to shear deformation within the Moyar and Bhavani shear belts. Two types of retrogression have been noticed. (1) Retrogression along shear planes, and (2) Retrogression along pegmatitic veins.

Initial stages of retrogression results in the formation of irregular, 2-3 cm to one meter wide bleached zones with the removal of greasy grey colour of charnockites. Minor structures which were earlier obscured in charnockites are clearly seen in bleached areas. In intensely shear areas, formation of highly fissile grey gneiss results often with the development of flaser and mylonitic structures.

Occurrence of pseudotachylites confined to areas adjacent to the Nilgiri granulite terrane and the shear belts suggest to their formation related to the upliftment of Nilgiris. Pseudotachylites show fine grained texture with feldspar+ quartz+biotite. Presence of a melt phase is noticed. It is not clear whether these pseudotachylites represent product of cataclasis or frictional fusion[2].

Petrographic observation of gneisses within the shear zone show breakdown of granulite facies mineral assemblage. Garnet exhibit cataclastic texture, traversed by veins of chlorite, and biotite. They exhibit symplectitic intergrowth with plagioclase and quartz. Both ortho and clinopyroxenes show alteration to greenish blue hornblende, actinolite, cummingtonite/grunerite, and biotite. Plagioclase show alteration to epidote and talc. Relict granulitic texture is noticed in some thin sections studied despite intense retrogression. As a result of pronounced deformation and shearing, quartz grains are flattened, and occur as ribbon like bands when compared to polygonal texture of quartz noticed in Nilgiri charnockites.

Fluid inclusion studies and geochemical investigations carried out for serial samples collected from charnockite to gneiss indicate following features: (1) There is a gradual decrease in density of CO_2-rich fluids from 1.073 to 0.821 g/cm^3(Fig.1). (2) Interestingly, in many sections of the gneisses studied, there is almost complete absence of fluid inclusions suggesting that they would have decrepitated. This may be due to large pressure difference (2-3 Kb.) created between the interior and exterior of the fluid inclusions[3], (3) Presence of mixed CO_2-H_2O inclusions were noticed. (4) Presence of low salinity (2-14 wt.% NaCl equivalent) bi-phase H_2O-rich inclusions (0.925-0.725 g/cm^3) suggest re-hydration during retrogression. (5) Fluid inclusion studies in quartz pegmatites indicate presence of low density CO_2-rich inclusions (0.840-0.659 g/cm^3) as well as H_2O-rich inclusions (0.900-0.525 g/cm^3).

Geochemical studies suggest depletion of Al_2O_3, FeO, MgO and CaO, and enrichment of SiO_2, Na_2O, K_2O, Rb and Sr. REE patterns studied for one pair of charnockite and gneiss show enrichment of LREE and strong depletion of HREE in the gneiss. However, in some of the samples studied, metasomatism appear to be insignificant during retrogression of charnockites.

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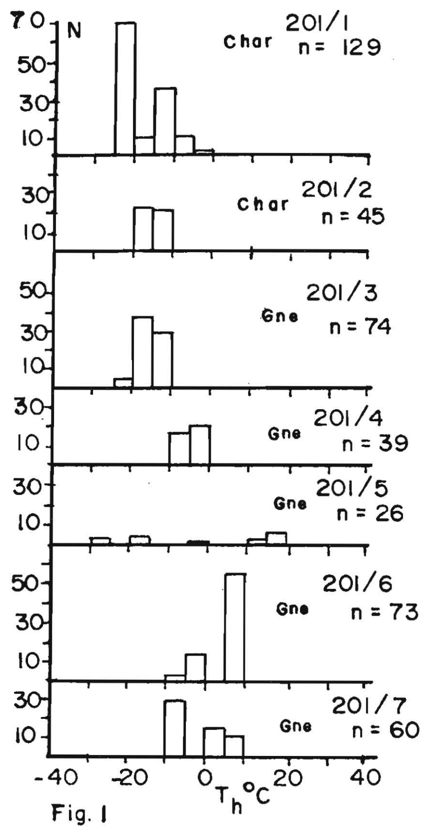

Fig.1 Temperature of homogenisation (T_h) of CO_2-rich inclusions for serial samples from charnockite to gneiss, Moyar shear belt. Char. = charnockite, gne. = gneiss.

PETROLOGY AND GEOCHEMISTRY OF THE HIGH-PRESSURE NILGIRI GRANULITE TERRANE, SOUTHERN INDIA

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The Nilgiri granulite terrane in Southern India is predominantly composed of late Archaean medium- to coarse-grained enderbitic to charnockitic rocks. The dominant regional foliation strikes N60-70E with generally steep dips. Tight minor isoclinal folds have been observed in places. Granoblastic polygonal microstructures are common and indicate thorough post-kinematic textural and chemical equilibration at conditions of the granulite facies (2.5 Ga ago (1)). The typical silicate assemblages of enderbites and charnockite are: plag+qtz+opx+gar+bio, plag+qtz+opx+hbl,cpx and plag+kfsp+qtz+opx+gar+bio. Late compressional deformation in connection with the formation of the Moyar and Bhavani shear zones to the north and south of the Nilgiri block, resulted in wide-spread development of weakly to strongly strained fabrics and was accompanied by minor rehydration.

Enderbites and charnockites range from tonalitic to granodioritic in composition. A magmatogenic origin of the protoliths is inferred from their chemical characteristics which resembles those of the andesitic to dacitic members of Cordillera-type calc-alkaline igneous suites .Their low abundances of U, Th, Rb, Zr (2 and this work), however, may be due to LILE depletion in connection with granulite facies metamorphism.

A significant lithological feature of the Nilgiri granulite terrane are numerous extended bodies, lenses and pods of gabbroic and pyroxenitic rocks which are aligned conformable to the foliation of the enderbite-charnockite complex and which have also been deformed and metamorphosed at granulite facies conditions (3).

The common pyroxenitic rocks are coarse-grained orthopyroxenites, websterites, hornblende- and garnet-hornblende pyroxenites with the following silicate assemblages: opx+cpx,hbl,plag; cpx+opx+hbl+plag,bio; hbl+opx+cpx,plag and cpx+opx+gar+hbl+plag, bio. The isolated occurrence of the pyroxenitic rocks and their chemical similarity with picritic basalts suggest that they could represent metamorphosed picritic dykes or sills rather than ultramafic cumulates (3). The low FeO^t, Cr and Ni abundances indicate fractionation of chromite and olivine from the parental magma. There is no compositional transition to the gabbroic rocks of the area.

Field relations, petrographic and geochemical characteristics allowed to distinguish two major groups of gabbroic rocks: (group 1) gabbroic to anorthositic two-pyroxene-plagioclase rocks, possibly representing fragments of differentiated igneous bodies and (group 2) ferroan garnet-pyroxene-plagioclase rocks constituting an individual series of NE-SW trending dyke-like gabbroic intrusions. Mafic granulites of this type occur also in the adjacent Moyar and Bhavani shear zones. The common silicate assemblages are: (group 1) cpx+opx+plag+hbl+bio,kfsp; cpx+plag+hbl+bio and (group 2) cpx+opx+gar+plag+hbl+qtz,bio.

The lithological features and chemical variation of the two-pyroxene-plagioclase rocks (group 1) can be attributed to cumulus processes involving clinopyroxene and plagioclase. There are striking similarities in major and trace element abundances to the gabbros and anorthositic gabbros of the Bhavani layered complexes (4). The mafic garnet-pyroxene-plagioclase rocks (group 2) exhibit a moderate iron enrichment tholeiitic trend and have distinctly higher FeO^t and lower Al_2O_3 contents than the gabbroic rocks of group 1.

Apart from these gabbroic rocks, several bands of completely undeformed clinopyroxene-plagioclase-(olivine) rocks with conspicuous ophitic texture and relic igneous mineralogy represent a set of late dolerite dykes which were emplaced into the enderbite-charnockite complex after the main period of penetrative deformation but still at conditions of the granulite facies. This is evidenced by the formation of garnet coronas on plagioclase, clinopyroxene and opaque phases.

Metasediments are rare in the Nilgiri granulite terrane and confined to bands and lenses of light garnetiferous gneisses, kyanite- and garnet-bearing quartzites and banded magnetite quartzites with garnet and ferrohypersthene.

Recent isotope studies (1) on granulites of the Nilgiri massif indicate that granulite facies metamorphism occurred about 2.5 Ga ago and closely followed the emplacement of the igneous protoliths. These findings together with the available field, petrographic and geochemical criteria lead us to interpret the Nilgiri granulite complex as a Cordillera-type plutonic belt generated through northward subduction and welded to the Archaean Dharwar craton in the north during early Proterozoic times. Accordingly, the Moyar shear zone represents a major tectonic suture.

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GEOCHEMICAL CHARACRTERISTICS OF CHARNOCKITE AND HIGH GRADE GNEISSES FROM SOUTHERN PENINSULAR SHIELD AND THEIR SIGNIFICANCE IN CRUSTAL EVOLUTION.:Dr. E.B.SUGAVANAM & K.T.VIDYADHARAN.

All the world over the stable shield areas are of high grade gneiss-granulite rocks occuring in close proximity with low grade granite-greenstone belts. The southern Peninsular shield exposes one of the largest high grade gneiss- charnockite terrains extending between Orissa in the north-east and Cape Comorin in the South. The high grade terrain in the south is in juxtaposition with the prominant granite-greenstone belts of Karnataka craton. The relationship between the low and high grade regions are not well understood. Greater attention has been paid to study the granite-greenstone belts of Karnataka craton compared to the adjoining granulite belts.

These shields are considered to represent ancient continental nucleii composed of the earlier crustal materials. Detailed studies of these terrains in different parts of the world contributed valuable clues to the evolutionary history of different parts of the earth's crust. Extensive work has been carried out on various aspects of petrology, petrochemistry, mineral chemistry, geochemistry and geochronology in major shield areas in other parts of the world. In contrast to these studies, much less information is available on the high grade regions of southern Peninsular shield of India. A limited study has been carried out on the charnockites of Pallavaram, the "type area" near Madras as well as in selected areas of Tamil Nadu and Kerala. Archaean high grade complexes in some parts of the world are regarded as recrystallised sediments (Siderenko[14], Cheney and Stewart[2]) and volcanics (Bowes[1]; Viswanathan[18]; Naqvi et al.[9]). The natural corollary of this approach is to regard these high grade complexes as highly metamorphosed greenstone belts. On the other hand Tarney[17], Lambert et al.[6], based on chemistry, concluded that the gneissic complexes differ significantly from the granite-greenstone pluton association.

Archaeans of south India are divided as "charnockite province" with deep seated highly metamorphosed rocks and "non-charnockite province" (Fermor[3]). A broad metamorphic zonation between greenschist and granulite facies rocks of southern Karnataka craton is considered as the continuous metamorphic sequence resultant of prograde metamorphism (Pichamuthu[12]). Structural disposition of the granulite terrain as compared to greenstone-granite terrain of Karnataka suggest that Tamil Nadu-Kerala granulite represent the oldest Archaean province (Narayanaswami[10]; Radhakrishna[13]). Granulite terrain of south India is regarded as charnockitic "mobile belt" associated with granite-greenstone belt and the Peninsular Gneissic Complex of Karnataka (Swami Nath et al.[16]). A contemporaneous evolution of granulites and greenstone belts in south India is evidenced by their relatively similar ages (Katz[4,5]).Contrary to the above conclusion of Katz, based on geological and geophysical characteristics of the structural provinces in the south Indian shield, a crustal tilting and north-west continuity of Tamil Nadu-Kerala granulite terrain beneath Archaean Karnataka craton has been suggested (Subrahmanyam[15]).

In the south Indian shield, the quartzofelspathic gneiss, the supracrustal rocks, layered intrusions in the charnockite province have been intensely deformed, obliterating the original nature and fabric of diverse litho units. It is difficult to decipher whether the intercalations of litho units in these areas is due to supracrustal superposition or due to deformation and conformable intrusion.

The paper presents the results of detailed investigations encompassing externsive structural mapping in the charnockite-high grade gneiss terrain of North Arcot district and the "type area"in Pallavaram in Tamil Nadu supported by petrography, mineral chemistry, major, minor and REE distribution patterns in various lithounits. This has helped in understanding the evolutionary history of the southern peninsular shield. A possible tectonic model has also been suggested. The results of these studies have been compared with similar rock types from parts of Andhra Pradesh, Kerala, Sri Lanka, Lapland and Nigeria which has brought about a well defined correlation in geochemical characteristics.

The area investigated has an interbanded sequence of thick pile of charnockite and a supracrustal succession of "shelf type " sediments, layered igneous complex, basic and ultrabasic rocks involved in a complex structural, tectonic, igneous and metamorphic events. Detailed field studies could bring out a tentative chronological succession of the above events.

In Leake's[7] diagrams, using Niggli values, the dominant igneous character of charnockite from different areas is well established while the khondalites distinctly plot close to fields defined for pelitic, semipelitic aluminous clay derived rocks. In Tarney's[17] SiO_2 - TiO_2 plot, charnockite from all the areas, under reference, fall in well defined igneous fields comparable with that of calc-alkaline Archaean plutonic suite of rocks.

In K_2O - CaO, K_2O- Na_2O, MgO - Na_2O binary plots as well as in K_2O - Na_2O - CaO and Ab-An-Or ternary plots the charnockite from North Arcot, Salem in Tamil Nadu, Kollegal and Sargur in Karnataka, parts of Andhra Pradesh, Kerala, Lapland and Nigeria fall in tonalite-granodiorite field while majority from Andhra, Sri Lanka occupy granodiorite-quartz monzonite-granite fields. However, the charnockites from Pallavaram essentially occupy granodiorite-adamellite-alkali granite fields. These studies have established the igneous nature of the pre-charnockitic rocks and their compositional heterogenity, most characteristic of any shield area.

The charnockites and associated high grade gneisses occupy a calc-alkaline trend ranging from tonalite-granodiorite-adamellite to alkali granite in the 'AFM' as well as in Miyashiro's plots of FeO vs FeO/MgO and SiO vs FeO/MgO. The basic granulite and other mafic rocks delineate an iron enriched tholeiitic trend. Thus, the characteristic bimodal igneous nature of high grade terrain is well brought out with a felsic/calc-alkaline unit as dominant over mafic/iron enriched tholeiitic rocks.

In Pearce and Cann diagrams, using TiO_2, Zr and Y, basic granulites are found to be mainly "Ocean Floor Basalts" (OFB) with a few of them falling in "Calc. Alkaline Basalts" (CAB) and "Low Potash Tholeiite" (LKT) indicating "within plate" characteristics.

The trace element geochemistry points out tonalite-granodiorite characteristics of charnockite and tholeiitic characteristics of "Andean type"continental margin for basic granulites. Similarly, REE pattern studies from Pallavaram indicate enrichment of LREE and depletion of HREE in charnockites comparable to the plutons produced at "Andean type" continental margins and do not correspond to andesitic volcanics. REE characteristics of basic granulites compare well with "within plate" Archaean continental tholeiites and not with greernstone basic volcanics.

In a comparataive study of geochemistry of the charnockites from the areas, under reference, with the averages of similar shield terrains in other parts of the world, it is found that in K_2O - Na_2O - CaO plot, the charnockites of North Arcot, Salem, Nigeria and Lapland having tonalitic composition, plot within the area occupied by Canadian granulites, Kaapvaal tonalites and K-poor Amitsoq gneisses of Greenland. On the other hand, the potash rich charnockites from Pallavaram, Andhra Pradesh, Sri Lanka occupy the area defined by igneous-metamorphic rocks of USSR shield as well as the Amitsoq gneisses and younger Kaapvaal intrusives. The basic granulites from Tamil Nadu and Karnataka fall in the area occupied by Canadian and Swaziland greenstone rocks.

Thus the geochemical evidence indicates that the high grade terrains in Southern Peninsular Shield are not simply a pile of recrystallised sediments and volcanics nor they are just metamorphosed greenstone belts. .They form a pile of bimodal meta-igneous rocks, one being felsic/calc-alkaline and the other basic/Fe enriched tholeiitic in composition with felsic being the dominant component. Together they compare well with that of younger calc-alkaline comnplexes of Cordilleran type.

The mineral paragenesis of charnockite and the associated rocks from parts of Tamil Nadu, Karnataka and Andhra Pradesh conform to their formation transitional from upper amphibolite to lower granulite facies conditions. The different methods of geothermometry and geobarometry (Weaver et.al) uswing critical experimental curves and coexisting mineral assemblages clearly confirm to their formation between 700° C and 800° C at 5 to 7 Kb, with 8 Kb pressure and 850° C temperature, being the maximum P-T conditions for these areas. The data agree well with those recorded from other Precambrian granulite terrains.

As the geological setting and geochemical characteristics of greenstone belts of Karnataka craton have been found to simulate fossil "back-arc basin", the spatially juxtaposed granulite-high grade gneisses of south Indian shield can be considered to represent the fossil 'marginal arc'.

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STRUCTURAL PATTERNS IN HIGH GRADE TERRAIN IN PARTS OF TAMIL NADU AND KARNATAKA

Dr.E.B.Sugavanam & K.T.Vidyadharan

Detailed geological mapping in parts of Tamil Nadu and Karnataka has brought out vast areas occupied by highly deformed charnockite and high grade gneisses. These areas, similar to high grade shield terrains in other parts of the world have the impress of extensive tectonic reworking multideformation and polymetamorphism and are closely associated with layered ultramafics, "shelf type" sediments and different igneous events.

In North Arcot and Dharmapuri districts of Tamil Nadu and Kollegal taluk in Mysore district in Karnataka, charnockite is intensely cofolded with a supracrustal succession of layered ultramafics, pyroxene granulite, pink granolites, magnetite quartzite and khondalites. These areas have undergone five phases of deformation, five generation of basic dyke activities, four phases of migmatisation and two periods of metallogeny. Geochronological data ranges from 2900 m.y. to 750 m.y.

In working out the tectanostratigraphy of the above areas the basic dykes of different generations have served as major "time marker". In addition, the persistant strike continuity of linear bands of pyroxene granulite, pink granolite and magnetite quartzite has been of great utility in using them as "structural markers" for bringing out the complex structural history in these areas.

The regional 'F_1' folds are isoclinal asymmetrical with NNE-SSW axial trace, in which charnockite (2600 m.y.) and the supracrustals together with 'M_1' and 'M_2' migmatite and norite sills (d_1) are involved. ENE-WSW aligned open symmetrical 'F_2' folds affect the 'M_3' migmatites, Gingee granite (2450 m.y.) and (d_2) dykes. Thus 'd_2' dykes separate the granulite facies and amphibolite facies rocks. WNW-ESE trending 'd_3' dykes (2100 m.y.) transect both the granulites and amphibolite facies rocks but are faulted, sheared and saussuritised by N-S trending asymmetrical shear folds. The major N-S shears filled with mylonite, phyllonite, cataclasite and flaser rocks are related to this deformation. Regional warps on WNW-ESE axis mark the 'F_4' deformation and its interferance with earlier folds has resulted in development of prominent structural basins and domes. Swarms of E-W and N-S trending pre Cuddapah dykes (pre 1700 m.y.) (d_4) mark the period of cratonisation and crustal fracturing. NNE-SSW aligned 'F_5' shear folds coaxial with 'F_1' folds caused extensive crustal fracturing and development of regional zones of shearing, mylonitisation etc. Synkinematic with this deformation, emplacement of alkali syenite-ultramafaics and carbonatite (750 m.y.) took place. Regional retrogression of granulites and amphibolite facies rocks ensued due to fenitisation. Tinguaite, phonolite, trachyte and lamprophyre dykes (d_5) were emplaced across the alkali syenite, fenitised gneiss and granulites.

NEW AGE DATA ON THE GEOLOGICAL EVOLUTION OF SOUTHERN INDIA.

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Extended Abstract

The Peninsular Gneisses of Southern India developed over a period of several hundred Ma in the middle-to-late Archaean. Gneisses in the Gorur-Hassan area of southern Karnataka are the oldest recognized constituents: Beckinsale et al. (1) reported a preliminary Rb-Sr whole-rock isochron age of 3358 +/- 66 Ma, but further Rb-Sr and Pb/Pb whole-rock isochron determinations indicate a slightly younger, though more precise age of ca 3305 Ma (R.D.Beckinsale, pers. comm.). Many other Rb-Sr whole-rock isochron results for Peninsular Gneiss suites are within 100 Ma of 3000 Ma - summarised in (2). Some of these have initial 87-Sr/86-Sr ratios significantly higher than contemporaneous upper mantle sources, implying origins by some reworking of older crustal material in a major tectonothermal event at ca 3000 Ma.

It is well established that the Peninsular Gneisses constitute basement on which the Dharwar schist belts were deposited (3,4). Well-documented exposures of unconformities, with basal quartz pebble conglomerates of the Dharwar Supergroup overlying Peninsular Gneisses, have been reported from the Chikmagalur and Chitradurga areas (3,4), and basement gneisses in these two areas have been dated by Rb-Sr and Pb/Pb whole-rock isochron methods at ca 3150 Ma and ca 3000 Ma respectively (2). Dharwar supracrustal rocks of the Chitradurga schist belt are intruded by the Chitradurga Granite, dated by a Pb/Pb whole-rock isochron at 2605 +/- 18 Ma (2). These results indicate that the Dharwar Supergroup in the Chitradurga belt was deposited between 3000 Ma and 2600 Ma. A Pb/Pb whole-rock isochron date of 2565 +/- 28 Ma for Dharwar acid volcanic rocks north of the Honnali gneiss dome (2) might suggest diachronous development of the schist belts, but could reflect post-depositional disturbances, since the isochron is poorly fitted.

New Sm-Nd model age data [T-DM ages according to DePaolo's (5) model] for Peninsular Gneisses, Dharwar acid volcanic rocks, Chitradurga Granite and Sargur kyanite schists are consistent with existing chronological constraints for the evolution of the Karnataka Craton. T-DM model ages for Chikmagalur Granite [3.25 Ga], Chikmagalur gneiss [3.30 Ga], and Chitradurga gneiss

[3.15 Ga] are ca 100 - 150 Ma older than the Pb/Pb whole-rock isochron ages for the corresponding rock-units, probably reflecting the time interval between separation of crust-building material from upper mantle sources and the formation of the respective rock-units. However, the difference between T-DM model ages for the Chitradurga Granite [2.96 Ga] and the Dharwar acid volcanic rocks [2.99 & 3.06 Ga], and their corresponding Pb/Pb isochron ages [ca. 2.6 Ga.] is greater, ca 400 Ma, and indicates a significant contribution from reworked older continental crust in the petrogenesis of these younger acid igneous rock-units.

The basement to the Dharwar Supergroup, in addition to Peninsular Gneisses, consists of a suite of highly metamorphosed rocks of sedimentary and volcanic origin, designated the Sargur Group or supracrustal association, which occurs as inclusions within the Peninsular Gneisses.

Two kyanite schist samples of the Sargur supracrustal suite at Kodineer Katte give T-DM model ages of 3.09 Ga and 3.18 Ga. These results are closely comparable to a model age of 3.15 Ga for a Chitradurga gneiss sampled approx. 35 km to the SE. Sm-Nd model ages for pelitic sediments and metasediments have received much attention in recent years (e.g. 6), and the usual pattern is that for Archaean samples the Sm-Nd model age is generally very close to the depositional age, whereas in younger samples the model age usually exceeds the depositional age substantially (6). Sm-Nd model ages for pelites are generally regarded as providing a good estimate of the average crustal residence age of the sediment; in the Archaean it is inferred that most pelites represent first cycle sediments, derived from newly formed crust. The significance of the Sargur kyanite schist model ages is that they are substantially younger than the oldest known constituents of the Peninsular Gneiss Complex, and indeed demonstrate that these pelitic rocks can only have been deposited a short time prior to the emplacement of the precursors of the gneisses within which they are now found as inclusions. It has been considered that the Sargur supracrustal rocks might represent the earliest components of the Karnataka craton, but these results demonstrate that the deposition of at least some of the rocks assigned to the Sargur supracrustals post-dates early phases of the Peninsular Gneiss Complex. It remains to be seen whether there is any diachroneity in the development of the Sargur supracrustal association. Sm-Nd work is currently in progress on other Karnataka samples, including more Sargur rocks.

In addition to our study of the Chitradurga and Chikmagalur areas, we have carried out Pb isotopic analyses of samples of the Closepet Granite towards the southern end of its outcrop, and of the Peninsular Gneisses on either side of the granite.

The Closepet Granite is an elongate, arcuate body extending northwards from near the Tamil Nadu / Karnataka border, passing to the west of Bangalore, through Tumkur, and continuing beyond Bellary on a north-north-easterly trend. The southern end of the granite is in the transition zone between the charnockite terrane of Tamil Nadu and the amphibolite facies Peninsular

Gneisses of Karnataka. Friend (7) considers that formation of the Closepet Granite and development of the charnockites were almost synchronous events, based on observation of granite veins cross-cutting charnockitized Peninsular Gneisses, and of charnockite development overprinting some of the granite veins, relationships clearly exposed in the quarries at Kabbaldurga.

For this study, we have analysed suites of grey gneisses from Dasapandoddi and Agasanapura, respectively east and west of the Closepet granite outcrop, and suites of Closepet Granite samples from quarries at Ramnagaram (formerly Closepet), and from a traverse across the granite outcrop along the Tumkur - Bangalore road. Pb/Pb isochron results for these suites are as follows:-

Dasapandoddi Grey Gneisses	[7]	2529 +/- 32 Ma.	Model μ1	8.19
Agasanapura Grey Gneisses	[7]	2535 +/-152 Ma.	Model μ1	7.65
Closepet Granite	[8]	2578 +/-156 Ma.	Model μ1	7.95

Clearly the age results are very similar, although the Dasapandoddi isochron is a much more precise determination than the others. Together they suggest that a major tectonothermal event took place at ca 2500 Ma, but the substantial variations in model μ1 values (source 238-U/204-Pb ratios) indicate that the rock-units evolved from sources or precursor materials with significantly different U-Pb fractionation histories. On their own, the model μ1 values do not provide unequivocal evidence for the involvement of older continental crust in the petrogenesis of these rock-units, so that the assessment of the role and character of any older crust in the ca 2500 Ma event in south-east Karnataka will require additional data. Sm-Nd analyses on these suites and on samples of gneisses, granites and charnockites from the Kabbaldurga quarries are in progress.

Roy Goodwin may not be able to squeeze blood out of a stone, but if you want Pb from a rock, then he's the leading man. John Arden exacted Sm and Nd from the rock samples with menaces and HF. Our thanks to them both.

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NATURE AND INTERPRETATION OF FLUID INCLUSIONS IN GRANULITES

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Many granulites contain CO_2 rich high density fluid inclusions (carbonic fluids). This observation has led to the concept of "carbonic metamorphism", (1) the dry character of granulites being less explained by the absence of water ("vapor absent metamorphism") than by the presence of a CO_2-rich fluid phase which dilutes the water and lowers considerably its partial pressure. Recent observations have indicated however that the situation is much more complicated than initially assumed and that any interpretation must be carefully evaluated and discussed against other, independent evidence.

NATURE OF FLUID INCLUSIONS: Carbonic fluids are dominant in granulites, but their abundance vary greatly from a sample to another. Perfect "granulitic texture" (equant crystals with straight boundaries and many triple junctions at 120°) are normally devoid of fluid inclusions, which are destroyed during the solid state recrystallization inherent to this texture. In other rocks, fluid inclusion abundance vary from astonishing heights (at least 10 to 20% in volume in garnet of some Indian charnockites) to a few tens of inclusions in a 10 cm^2 double polished plate. Even if it is not possible to link the abundance of fluid inclusions and the absolute fluid quantity present at the time of their formation, this must indicate a very unequal fluid distribution during and after granulite metamorphism.

Most important, carbonic fluids are not the only fluids occurring in granulites. Other gaz components, notably CH_4 and N_2, have been observed, mixed or not with CO_2. Pure CH_4 and/or N_2 have always a very low density and they are obviously generated or reequilibrated at a very late stage of the rock history. This poses a serious problem for N_2, which, from its occurrence (most abundant in or near metasediments), seems to be inherited from a premetamorphic stage and must therefore have gone through the whole range of P.T. conditions.

Aqueous inclusions, present in variable amounts in many granulites, were initially assumed to be late and related to the partial retromorphosis shown by almost any granulites. This is certainly correct for late, low salinity, high density H_2O inclusions (homogenisation temperature below 200°C), but not obvious for high salinity, NaCl bearing brines which, in some granulites, are far more abundant than CO_2 inclusions. They are essentially related to specific lithotypes (metapelites, skarns, meta acid volcanics) and their distribution indicate that they may have coexisted with CO_2 (immiscible fluids) during and after peak metamorphism. (2)

INTERPRETATION OF FLUID INCLUSIONS DENSITY (ISOCHORES). This is a very complicated problem which can best be attempted for pure CO_2. Note that the maximum CO_2 density presently recorded with certainty is 1.176 g/cm^3, corresponding to a homogenization temperature (liquid) of -56.6°C (CO_2 triple point). All inclusions which homogenize at lower temperatures ("metastable extension of the liquid-vapor curve") precisely investigated so far are CO_2-N_2 mixtures. (3).

High density CO_2 inclusions tend to reequilibrate easily to changes in external P-T conditions. This is shown e.g. by many decrepitation features and extensive transposition of former inclusion trails along new directions. In some cases, a careful observation establishes a sequence of inclusion formation, from primary to several generations of secondary ones. Primary inclusions are especially abundant in some minerals, notably garnet and plagioclase, but they may also be found in unstrained minerals (e.g. quartz) totally enclosed and protected in another larger mineral grain (e.g. quartz in garnet or plagioclase). Contrary to earlier hypothesis (4), it has been found that successive generations do not systematically correspond to a decrease of inclusion density. This complicates obviously the interpretation of fluid inclusion data (highest density inclusions cannot be longer considered as closest to peak metamorphic conditions) and, in order to characterize a synmetamorphic fluid, several conditions must be fulfilled:

1) *A well defined isochore, corresponding to a precisely identified generation of fluid inclusions, must be consistent with a set of P.T. conditions derived from coexisting minerals (Intersection of the isochore and the P.T. "box" of a given metamorphic assemblage).*

2) *Later inclusions in the same sample must fall on isochores differing significantly from the one corresponding to early inclusions.*

The trend of variation (evolution towards higher or lower densities) defines 2 major types of possible post metamorphic P.T. trajectories:

i) "Adiabatic uplift path", in which pressure decreases faster than temperature (essentially vertical movements, decrease of density with time). (4)

ii) "Isobaric cooling path" showing an opposite trend and an increase of CO_2 density in younger inclusions. (2)

Two examples are discussed in some detail: West Uusimaa Complex (Finland), a low pressure granulite dome illustrating the first trend (isobaric uplift) and a mylonitic charnokite of Dodda Betta, India, in which 3 successive generations of CO_2 inclusions in garnet, plagioclase and quartz show a density increase from 0.96 g/cm^3 in garnet to 1.12 g/cm^3 in quartz. It is suggested that the isobaric cooling trend can be due, either to the intrusion at depth of deep seated, synmetamorphic intrusive masses, or to large scale horizontal thrusting.

3) *The nature of the fluid must correspond to the theoretical composition predicted from heterogeneous mineral equilibrium.*

At a time where thermodynamics and the theory of mineral equilibria allow the prediction of many fluids, this condition may seem obvious. It must be recognized, however, that it has up to now met with a limited success and that, in many cases, the observed composition differs grossly from the expected one: CO_2 in wollastonite skarns (Willesboro, New Jersey), CO_2 in rocks where the combination of fO_2, P and T should indicate more reduced species, etc. (5)

Each case must be discussed seperately, but there are at least some possible answers for many observed discrepancies:

i) In the lower crust, fluid composition may be locally buffered and vary markedly on short distance. This may result in apparently immiscible mixtures of e.g. brines and CO_2, a situation which has been obscured in many metalimestones and skarn related occurrences (2). It is possible that the CO_2 observed in Willesboro samples represent an externally derived droplet in the real metamorphic fluid, a brine.

ii) Many systems are not internally buffered for fluid composition. This is the case e.g. for charnockites, in which CO_2 was most probably introduced in the magmatic stage, either as dissolved gazes or from the breakdown of carbonate melts (2,6). If oxygen fugacity is buffered by the QMF assemblage CO_2 is the dominant species at 7 kb total pressure for temperatures above 600°C (Fig. 10, in 5). Lower fO_2 will drastically decrease the CO_2 content, and at QMF-2 log units, for instance, CO_2 is only dominant at temperature above 900°C. Many fO_2 recorded by opaque assemblages correspond to the CO_2 absent field, but only at temperature well below any possible peak metamorphic temperature. Conversely, the few results which correspond to peak temperatures (about 800°C) are frequently above the graphite stability line and hence consistent with a CO_2 fluid.

In conclusion the interpretation of fluid inclusions in granulites is a difficult problem which requires several conditions:
- Favourable samples: Possibility to establish inclusion chronology, lack of obvious perturbation and recrystallization.
- Very careful observation and comparison of fluid and solid mineral data at the scale of the hand specimen. P-T solid estimates and fluid inclusion investigations must be done in the same specimen and, ideally, in the same thin section.
- Absolute necessity to discuss the fluid inclusion information against other independent evidences. It must be remembered, however, that any solid assemblage may evolve after its crystallization and that fluid inclusions are not a priori more sensitive to external perturbation than rock forming minerals.

Once these limitations and difficulties are accepted, it becomes evident that the potential information contained in fluid inclusions and in the associated minerals is of prime importance for the interpretation of the rock history. Analytical techniques and theoretical background are now sufficiently well established. Only the multiplication of precisely studied cases will help to understand fully their message.

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GRANULITES: MELTS AND FLUIDS IN THE DEEP CRUST

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Known examples of granulite facies metamorphism span at least 3.5 by. of Earth history. Mineralogic geobarometry indicates that such metamorphism has occurred in the deep crust, typically at 20-30 km (6-9 kbar). Geothermometry indicates that peak T = 700-900°C and therefore that T was elevated by at least 200°C over an "anorgenic" geotherm of 15-20°C/km. Commonly invoked sources of heat include rising magmas, radioactive decay insulated by continent/continent collision, mantle volatiles, or crustal thinning. Present day crustal thicknesses are normal beneath exposed granulite terranes and the common absence of evidence for post-metamorphic underplating suggests syn-metamorphic thicknesses of 60-80 km. Thus granulites form in tectonically active regions of thickened crust and elevated geotherm. Xenolith suites suggest that granulite facies mineralogy persists in the deepest crust after tectonism in spite of declining temperature to greenschist/amphibolite facies conditions.

Dehydration is a universal characteristic of granulite terranes with quantitative estimates of H_2O activity = 0.1 ± 0.1. Complexity and local variability of fluid conditions has been well documented in some terranes. Proposed explanations of low αH_2O include: 1. melting and selective removal of H_2O in magmas; 2. passage of dry magmas derived at greater depth; 3. metamorphism of already dry rocks (igneous or metamorphic), and 4. streaming of mantle CO_2. Controversy surrounds the relative importance of each process. In 1.1 by. granulites from the Adirondack Mountains, N.Y., many rocks were metamorphosed in the absence of any free fluid phase due to processes 1, 2 and 3.[1-3,5] Such fluid-absent metamorphism contrasts strongly with evidence from Archaen granulites in S. India indicating large quantities of CO_2 streaming and total CO_2/rock ratios of 0.1 - 0.5.[4] High density, CO_2-rich fluid inclusions are cited as evidence for syn-metamorphic CO_2-streaming in many terranes, however petrologic results from the Adirondacks show that such inclusions post-date granulite metamorphism.[3] Overpressured CO_2 densities in CO_2 and CO_2-H_2O bearing inclusions indicates that post-metamorphic P-T paths were concave towards T.[3]

The relative proportions of granulite terranes that are formed by 1. Adirondack-type metamorphism (dominantly magmatic/fluid-absent), 2. India-type metamorphism (CO_2 saturated), or 3. some combination of 1. and 2.[5] remains an important tectonic question. Limits to the scale of CO_2 streaming may be estimated by analysis of: 1. common occurrences, worldwide, of low $\delta^{13}C$ graphite, scapolite, and cordierite, 2. the mass flux of CO_2 required to dehydrate the crust which may exceed 10^{14} grams/year, 3. wide-spread evidence of melting in granulites.

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UNDERPLATING, ANATEXIS AND ASSIMILATION OF METACARBONATE; A POSSIBLE SOURCE FOR LARGE CO_2 FLUXES IN THE DEEP CRUST. S. M. Wickham, Department of the Geophysical Sciences, University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637

Recent models for granulite petrogenesis have involved infiltrative streaming of CO_2 derived from deep-seated sources,[1] removal of H_2O in locally generated silicate melts[2,3], or various combinations of these two processes.[4,5] All these models require a heat source of some type to generate the high crustal temperatures associated with anatexis and granulite-grade metamorphism, and this most likely takes the form of mantle-derived basaltic magma that is either underplated or intruded into the lower continental crust. Huppert and Sparks[6] have recently shown that such underplating is likely to cause rapid, very large-scale melting of the overlying crust (roof rock) over time scales of only a few hundred years (e.g., a basaltic sill 500 meters thick can generate a melt layer between 300 and 1000 meters thick in less than 500 years, depending on the initial temperature of the crust). Refractory rocks within the melt layer, such as carbonate-rich metasediments, would not melt, but are expected to sink into the underlying mafic magma. Calculations indicate that for plausible rock compositions (e.g., amphibolite facies diopside marbles) the thermal energy of the mafic magma would be enough to promote very high temperature decarbonation of large volumes of marble ($T > 850°C$), generating sudden, large fluxes of CO_2-rich fluid that would be released upwards through the anatectic zone into the overlying crust. Such a process could explain many petrological features of those granulite terranes where CO_2-streaming is thought to be important, and may also be an underlying cause of commonly observed surface emanations of CO_2 at volcanic centers associated with extensional tectonism (e.g., in the Massif Central). The isotopic composition of such emanations is readily interpretable in terms of derivation from deep-seated metacarbonate rocks.

This model is readily applicable to the granulite terrane of Southern India where metacarbonates occur within the deeper parts of the section including the amphibolite-granulite transition zone.[7] Furthermore, it obviates the need to remove low melt fractions from deep crustal rocks as a principal dehydration mechanism; compaction theory has shown this to be a very sluggish process that is unlikely to be important over typical geological time scales.[8] It also avoids any mechanism involving the subduction of large volumes of sedimentary carbonate into the mantle to provide a CO_2 source. Whether or not CO_2-flushing occurs during granulite-grade metamorphism of the lower crust may simply reflect the presence or absence of carbonate rocks within the zone of major anatexis (i.e., at those crustal levels immediately adjacent to an intruded/underplated mafic layer). CO_2 fluxes generated in this way may be a natural consequence of crustal growth processes involving underplating of mantle material beneath a carbonate-bearing lower crust.

METAMORPHISM OF THE ODDANCHATRAM ANORTHOSITE, TAMIL NADU, SOUTH INDIA. R. A. Wiebe, Dept. of Geology, Franklin and Marshall College, Lancaster, PA, 17604 and A. S. Janardhan, Dept. of Geology, Manasa Gangotri, Mysore 6.

The Oddanchatram anorthosite [1,2] is located in the Madurai District of Tamil Nadu, near the town of Palni. It is emplaced into a granulite facies terrain commonly presumed to have undergone its last regional metamorphism in the late Archean about 2600 m.y. [3]. The surrounding country rock consists of basic granulites, charnockites and metasedimentary rocks including quartzites, pelites and calc-silicates. The anorthosite is clearly intrusive into the country rock and contains many large inclusions of previously deformed basic granulite and quartzite within 100 meters of its contact [2]. Both this intrusion and the nearby Kaduvar anorthosite show evidence of having been affected by later metamorphism and deformation.

The anorthosite is typical of Proterozoic anorthosites in that it is largely massive and coarse-grained, containing on average more than 90 percent plagioclase (An_{50-51}) and has associated lenses rich in Fe-Ti oxides. Plagioclase is variably recrystallized: it generally displays abundant, strongly curved secondary twinning and has strongly sutured boundaries. The most common mafic minerals are hornblende, augite and orthopyroxene. Hornblende and some pyroxenes probably crystallized during metamorphism, but some pyroxene also occurs in primary igneous textures. Garnet occurs locally as equant crystals in thin discontinuous bands, but has not been found as a reaction rim between plagioclase and pyroxene. Although delicate primary igneous features are locally well preserved, this anorthosite appears to have been strongly affected by deformation and metamorphism after its emplacement. The rocks do not appear to have suffered significant strain after the growth of garnet.

Intrusive contacts of the anorthosite with the surrounding country rock are well exposed. Sharply bounded dikes of relatively fine-grained anorthosite occur at a few locations; some are tightly folded. Anorthosite near the contact commonly contains abundant elongate inclusions of basic granulite and lesser amounts of garnet-bearing quartzite. Post-emplacement deformation is indicated by a locally strong penetrative fabric and by boudinage of some inclusions. Assimilation of metasedimentary rocks appears common along some portions of the contact: where calc-silicate rocks have been incorporated the anorthosite is abnormally calcic and where pelitic rocks have been incorporated the anorthosite contains discontinuous zones with disseminated quartz and equant garnets [2]. Most garnets are partly or completely replaced by delicate symplectites of hypersthene and anorthite.

Mineral assemblages useful for thermobarometry are found in the anorthosite and in the surrounding country rock.

Anorthositic rocks locally contain garnet, quartz, orthopyroxene and clinopyroxene in addition to the dominant intermediate plagioclase. Pelitic country rocks contain an early assemblage of rutile, garnet, sillimanite, and quartz which has partly reacted to produce prominant rims of cordierite between garnet and sillimanite. A charnockite located roughly two km south of Oddanchatram contains the assemblage, quartz-plagioclase-orthopyroxene-garnet.

Although some garnets in anorthosite lack symplectite rims and occur in sharp contact with primary intermediate plagioclase, they more typically have broad, essentially unzoned cores and narrow rims depleted in Ca where they are in contact with surrounding symplectites of orthopyroxene and anorthite. Garnet in the pelitic rocks is much lower in grossularite component and essentially unzoned. In the charnockite it is also unzoned and very low in MgO. Orthopyroxenes in anorthositic rocks have Mg/(Fe+Mg) of roughly 0.55. Neither pyroxene is significantly zoned. Orthopyroxene in the charnockite has much lower Mg/(Mg+Fe). Primary plagioclase in the anorthosite ranges from about An46 to An55. Plagioclase in the symplectites is between An95 and An85. In the charnockite it is An34.

Metamorphic equilibration temperatures in the anorthosites, based on coexisting garnet and clinopyroxene, range from a maximum of about 920°C to about 700°C. It has not been possible to determine a maximum temperature of metamorphism in the country rocks. The assemblage, garnet-cordierite, is widespread in the pelitic rocks but is retrogressive. These minerals are essentially unzoned and yield temperatures between 780 and 700°C - temperatures that closely match the minimum temperatures recorded by symplectites in the anorthosite. The relict assemblage, garnet-sillimanite-quartz-rutile, could have been stable at much higher temperatures.

Estimates of pressures within the anorthositic rocks are based on the association of garnet-plagioclase-quartz with orthopyroxene or clinopyroxene. Garnets that lack symplectite rims and the cores of other garnets yield estimates of about 11.3 kb at 920°C. Garnet rims in equilibrium with surrounding anorthite-hypersthene symplectites yield estimates of from 7.3 to 5.6 kb at 775°C. Pressures estimated for the pelitic rock are based on the retrogressive assemblage, garnet-cordierite. The model of Aranovich and Podlesskii [4] yields pressures of from 7.7 to 7.2 kb. These pressures are consistent with the minimum values recorded by symplectite assemblages in the anorthosite. The relict assemblage, garnet-sillimanite-quartz- rutile, could have been stable at the highest pressures and temperatures determined for the anorthosite. In the charnockite, the assemblage, quartz-plagioclase-orthopyroxene- garnet, yields an estimate of 8.8 kb, assuming a temperature of 900°C.

Because the Oddanchatram anorthosite should be similar in age (ca. 1400 my) to the Chilka Lake anorthosite [5] the metamorphism of the Oddanchatram anorthosite should record crustal conditions in this part of the south Indian shield during the middle to late Proterozoic. Temperatures and pressures reported for other rocks in this portion of the shield (e.g. rocks near Madurai and Kodaikanal [6]) may therefore be a record of Proterozoic rather than late Archean metamorphism.

The maximum pressures reported here require that Archean supracrustal rocks in the southeastern portion of the south Indian shield were buried to depths of 35 km in the middle Proterozoic. Because the present crustal thickness is still about 40 km [7] and because there is no evidence for post-anorthosite underplating, the crustal thickness in this part of the shield during the middle Proterozoic should have been roughly 75 km. The production of such abnormally thick crust could be explained by continental collision and underthrusting of the eastern margin of the south Indian shield beneath a converging continent. The Eastern Ghat orogenic belt, which lies roughly 100 km east of the Oddanchatram anorthosite, is thought to be such a mid-Proterozoic collisional belt [8]. Metamorphic mineral ages of 1000 my [9] in this belt suggest that the Eastern Ghat orogenic event could have been responsible for the metamorphism and deformation of the Oddanchatram anorthosite.

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FIELD GUIDE

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PART I

GEOLOGY

SUMMARY

The Indian Precambrian continental crust exhibits a variety of geological features fashioned at different times by different geotectonic processes. The bulk of this crust was formed prior to 2600 m.y. ago and remobilized at least twice between 2600-2000 m.y. ago (early Proterozoic Mobile Belt, EPMB) and 2000-1500 m.y. ago (middle Proterozoic Mobile Belt MPMB). Three early Precambrian nucleii: Karnataka (KN), Jeypore-Bastar (JBN), and Singhbhum (SN) appear to have survived in the craton and are characterized by low-grade supracrustals and tonalitic to trondhjemitic gneisses, formed 3800-2600 m.y. ago. The EPMB event involved sedimentation, amphibolite-granulite facies metamorphism, and CO_2-K metasomatism and produced amphibolite facies rocks and K-granites in the north, and charnockite and other granulite facies rocks in the south. Gold sporadically distributed in the supracrustal rocks of the craton was remobilized during the EPMB event. K-granites form a garland around the central Dharwar craton, suggesting some type of collision between two blocks. The compressional stress directions in the craton and the surrounding mobile belts were EW, producing almost identical structures in all the regions. The supracrustals of the Indian Archaean are broadly divisible into an older and a younger sequence . Older belts are characterized by argillites and chemogenic sediments

of high Mg, Fe, Al, Cr, and Ni abundances, while younger belts are characterized by graywacke-shale suites with abundant Na, K, Rb, and Sr. The REE, U, and Th abundance patterns of the two groups show significant differences. The small amount of ultramafic rocks in the Indian Precambrian necessitates alternative sources for the high Ni and Cr contents in the supracrustals. Cr and Ni contents are high even in gneisses of this region. The available data provide constraints for a model which suggests that older schist belts were developed in shallow water basins on a simatic crust. On the other hand, the platformal components of the younger greenstone belts were laid down in rifted basins on a sialic basement. Crustal deformation and thickening gave rise to the EPMB.

At 2000-1500 m.y. ago, another intensive mobile belt event occurred in which subduction and flexure at the eastern northern margins of the Dharwar-Singhbhum Protocontinent gave rise to Proterozoic sedimentary basins, rift valleys, and igneous and metamorphic suites. Plate tectonic regimes had clearly set in by 2000 m.y. ago; the middle Proterozoic orogeny shows clear evidence of modern-style collision tectonics. (Radhakrishna and Naqvi 1986).

1. GENERAL GEOLOGY

Studies of Precambrian terrains in the last two to three decades have given a picture of "granite-greenstone" continental nuclei, bordered by high-grade intensely deformed "mobile belts". The cratonic nuclei are essentially made up of tonalitic to trondhjemitic gneisses, enclosing elongate eugeosynclinal volcanic-meta sedimentary basin (older and younger greenstones), with late "anorogenic" K-rich granites intruding them. On the other hand, the bordering mobile belts are complexly deformed and contain granulite facies gneisses and charnockites (Early Proterozoic mobile belts, Radhakrishna and Naqvi, 1986). Significantly, it is in these latter belts, or in their peripheral zones, enclaves of older high-grade supracrustals with continental marginal affinities (pelite-marble-quartzite-BIF) occur.

The Precambrian terrain of south India (Fig.1) contains all these units in a compact manner. In fact, all the units can be best studied in southern Karnataka, in N-S traverse from Chitradurga to Mysore. South of Mysore, near Sargur, older supracrustals (> 3000 m.y.) occur as enclaves within amphibolite facies gneisses. Further south, the arcuate Biligirirangan - Nilgiri -

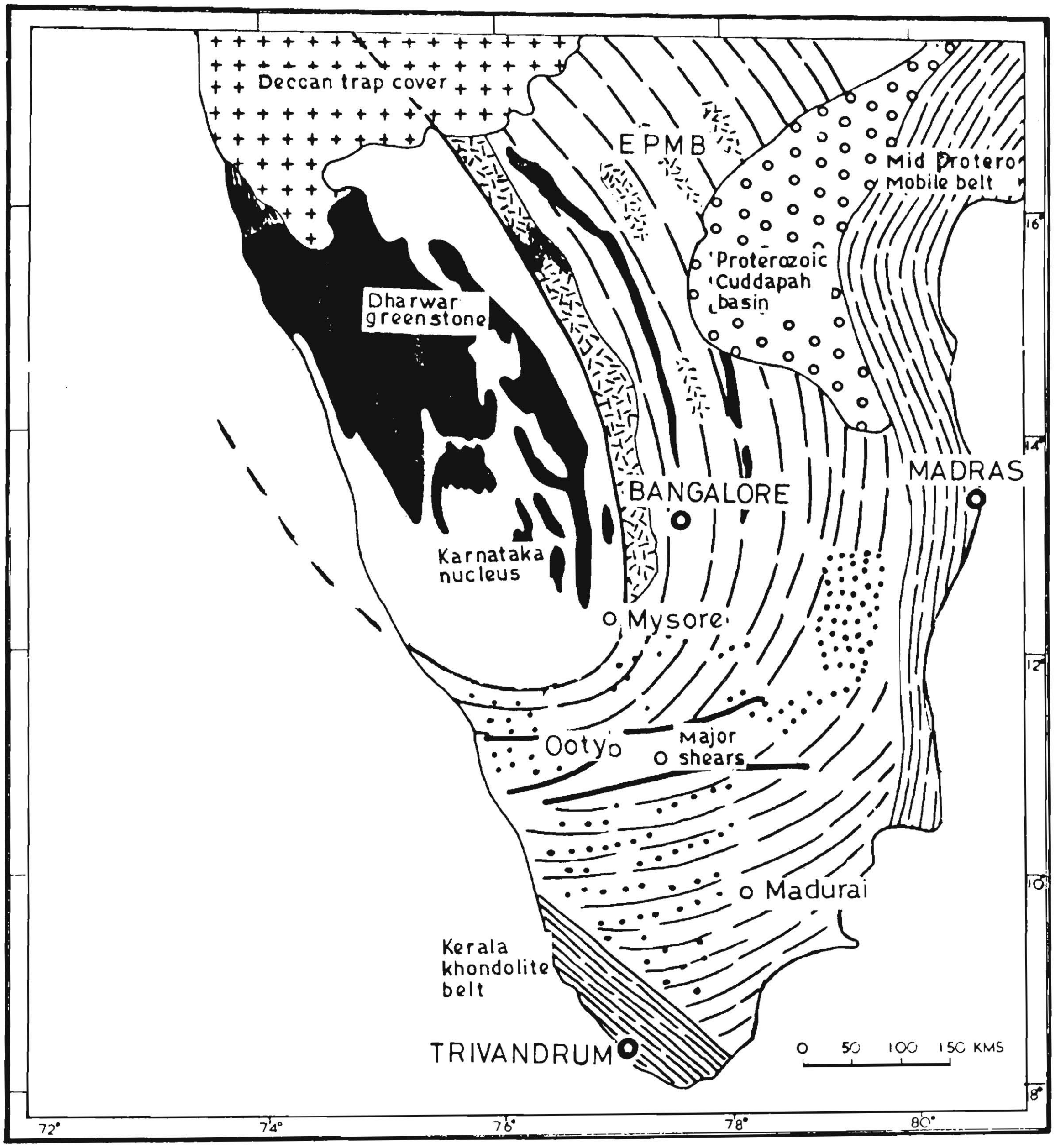


Figure 1. Sketch map of the Precambrian terrane of South India.

Coorg Hill ranges are made up of granulite facies charnockites. There is a view that the high-grade terrains are older and that the supracrustal enclaves in them are different from those recognized within the greenstone-granite terrain.

Significantly, in southern Karnataka the enclaves of older supracrustals of continental platformal affinities can be traced well into the charnockite terrain, e.g., in the Biligirirangan hill ranges (Rama Rao, 1945) and in Coorg ranges (Gopalakrishna et al, 1986).

Table I

Generalized Chronology of Events in Southern Indian Shield

2600-2500 Ma	Major tectono-thermal event leading to granulite formation and late potassic granites.
2900-2600 Ma	Younger greenstones (Shimoga, Chitradurga, Sandur (Dharwar type) Lower mafic and felsic sequence with interbedded conglomerate, quartzite, BIF and greywacke.
3000 Ma	Main extent of migmatitic gneiss-older greenstones mainly volcanic complexes (Kolar type).
3400 Ma	Emplacement of older tonalite-trondhjemitic gneiss with enclaves of ancient supracrustals.
>3400 Ma	Ancient supracrustals with associated mafic and ultramafic rocks. Sediments consist of chemical precipitates and detrital origin (Sargur type?).
	Basement not recognised.

The Archaean terrain of southern India exposes an "apparently" continuous depth section of earth's early crust, thus offering excellent opportunities for studying the problems related to the bimodal arrangement of an Archaean craton and (surrounding) mobile belt. The general calc-alkaline nature of the charnockites of the mobile belts represent the earliest form of marginal accretion. An alternative view is that the mobile belts pass beneath the continents as their "deep roots" (Kroner, 1980). The validity of these two models can be best tested in southern Karnataka, by studying the relation between the older Sargur supracrustals and the associated gneiss (Peninsular gneiss). The tectonic relationship between the two units - the younger Dharwar greenstone belts occurring further north and the charnockitic terrain to the south is expected to throw fresh light on this problem.

The granulite facies orthopyroxene "isograd" roughly starts at 12°45' N latitude. South of this isograd, the granulite facies charnockite and its retrogressed product - banded gneiss, make up the greater part of south India, including almost the whole of Tamil Nadu and Kerala states. The significant feature of this terrain is that charnockite massifs stand out as hill masses, viz., Niligiri; Shevaroy and Kodaikanal. Available isotopic ages are given below:

Madras - 2600 Ma (Rb-Sr, Crawford, 1969).

Salem - 2550 Ma (Rb-Sr, Pb-Pb, Vidal Pers.Comm, 1987)

Nilgiris - 2600 Ma (U-Pb of Zircon, Buhl 1987)

Coorg - 2600 Ma (Rb-Sr, Spooner & Fairbairn 1970)

Kabbal - 2560 Ma (U-Pb of Allanite, Grew and Manton 1986; U-Pb of Zircon, Buhl, 1987)

The available isotopic ages indicate that granulite event leading to the formation of charnockite took place around 2600 Ma.

The charnockites of southern Kerala have given younger ages of $\simeq$ 640 Ma (Srikantappa et al, 1985; Santosh and Iyer 1987). Ages of 1000 Ma (Grew and Manton, 1986) have been obtained for the granulite facies rocks of the Eastern Ghats suggesting younger granulite facies events in the areas of southern most Kerala and eastern Andhra Pradesh (Middle Proterozoic mobile belt of Radhakrishna and Naqvi, 1986). The charnockites occur inter-banded with swathes of khondalites (name given to a metamorphosed sequence of sediments ranging from pelites, garnet-silimanite-biotite-schist to carbonates).

The thrust of the workshop will be on granulite facies rocks, the nature and mechanism of their formation. The study has great implications on the thickening and stabilisation of the continental crust. The participants will have ample opportunities to study typical features of the following (see Fig.1)

1. Ancient Supracrustals (Sargur type) — ($\simeq$ 3400 Ma) ?

2. Kolar Greenstones and associated granites and gneisses — (3000 Ma)

3. Peninsular gneisses of 3000 Ma around Bangalore-Gundlupet and at Kabbal.

4. Charnockites of 2600 Ma.

   (a) Transition type at Kabbal and Satnur.

   (b) High pressure type around Ooty and the retrogressed product of charnockites in shear zones as at Masanigudi and Mettupalayam.

5. Younger potassic granites (Closepet) Ramanagaram and Kabbal.

6. Younger Charnockites and Khondalites: Southern Kerala.

2. ANCIENT SUPRACRUSTALS (SARGUR TYPE)

Ever since Foote (1900) grouped the schistose rocks of erstwhile Mysore State into the Dharwar system, there has been intermittent debate on whether some schists in southern Karnataka represented another older group separated in time from the Dharwars. The idea was concretised by the Geological Survey of India (Karnataka Circle) in the mid-seventies (Swami Nath and Ramakrishnan, 1981). Angular unconformities between Sargur enclaves in gneiss and Dharwar schist belts were demonstrated at several places confirming the presence of two distinct orogenic cycles, Sargur and Dharwar (Ramakrishnan and Viswanatha, 1987). It is now generally accepted that there are two distinct cycles of sedimentation one older and the other younger than 3000 Ma, the dividing factor being the widespread Peninsular gneissic complex of 3000 Ma. Some workers, however, still hold the view that the Sargur Supracrustals are part of the lower section of Dharwar succession (Pichamuthu and Srinivasan, 1984; Naha et al, 1986). A suggestion has been made that the wide spectrum of high-grade lithologies should be classified as Ancient Supracrustals representing in all probabilities sediments older than 3400 Ma gneisses, recognised in Karnataka (Radhakrishna, 1983).

The Ancient Supracrustals of Sargur are interlayered with Archaean quartzofeldspathic tonalitic to trondhjemetic

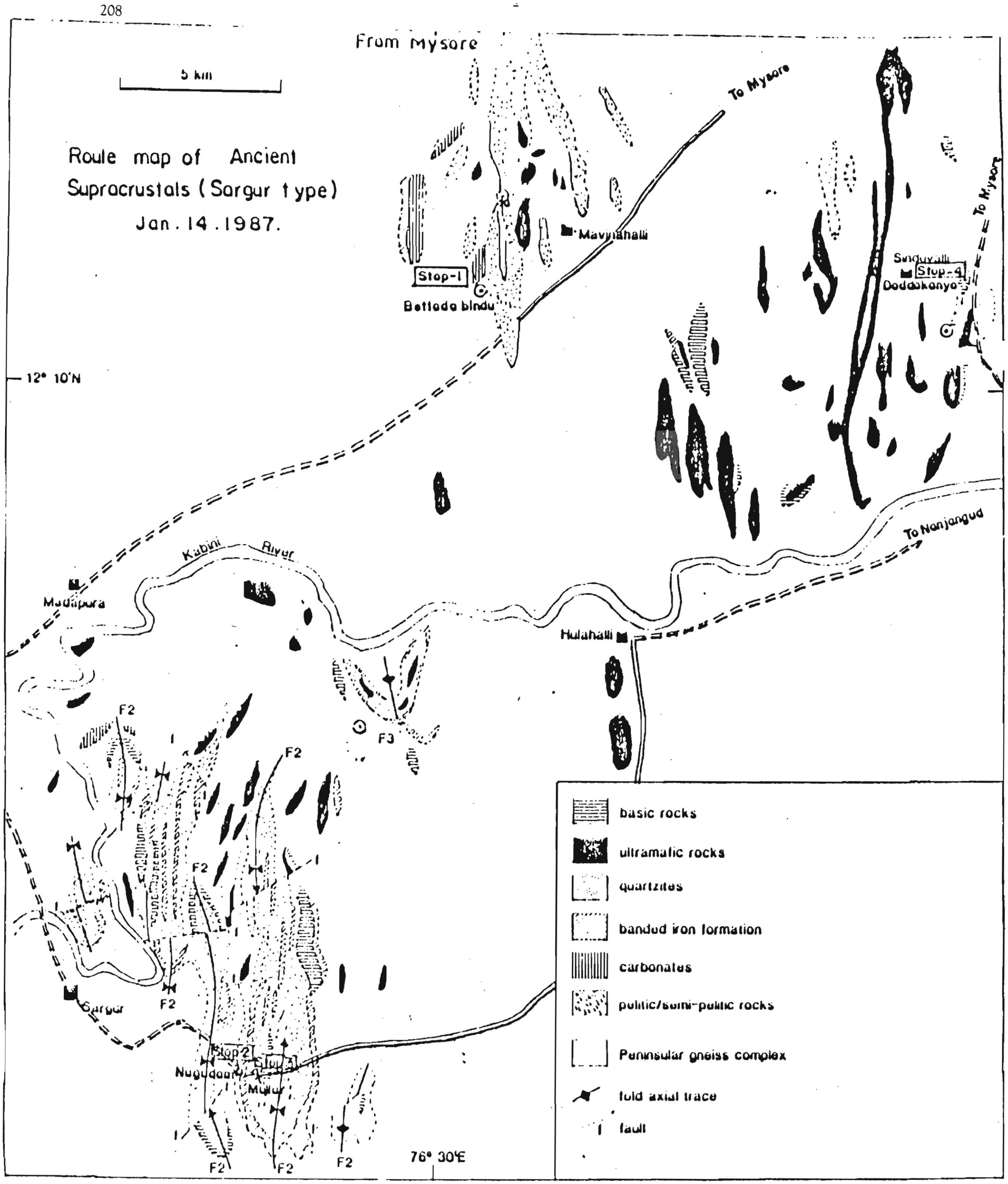


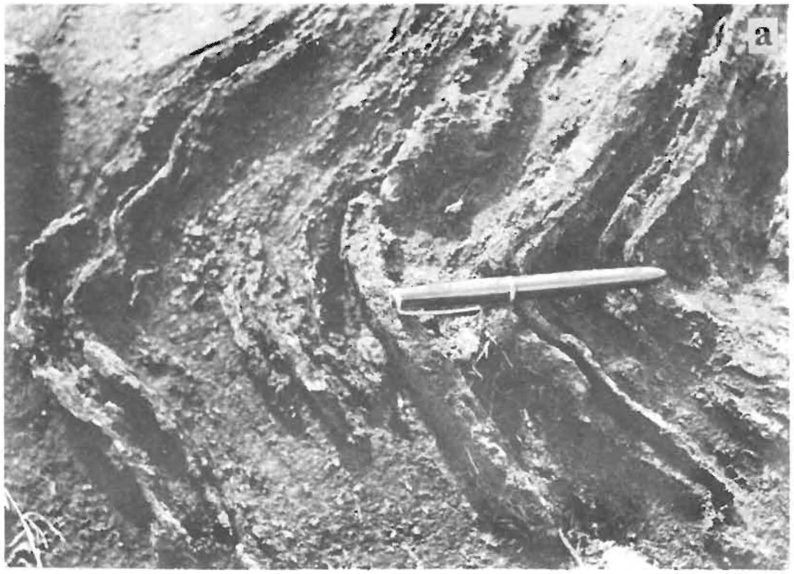
Figure 2. Ancient Supracrustals (Sargur type)

gneisses (2850 Ma - 3400 Ma Janardhan and Vidal, 1982; Buhl, 1987). They form tight to isoclinally folded remnants of quartzite - K-pelite - carbonate - BIF sediments (Plate I, Fig.'a'; Fig.'b'; Fig.'c') of continental marginal basin affinities (Janardhan et.al., 1978). The metasediments occur as bands 10-100m thick and over 2 km long within the gneisses. The bands have been intensely deformed and primary structures are generally not observed. The striking feature of this supracrustal association is its thinness, abrupt lateral variation, high grade metamorphism and repetition.

There are at least two recognisable episodes of basic magmatism. The first one is represented by amphibolites, which are now seen as bands interbedded with metasediments. Good examples of this can be seen at Nugu dam site where basic rocks are interbedded with BIF, and at Bettadabidu where carbonates are interbedded with amphibolites. The precursor rocks of these amphibolites exhibit low K-tholeiitic affinities (Table II) and have all the characters typical of Archaean tholeiites described by McGregor and Mason (1977).

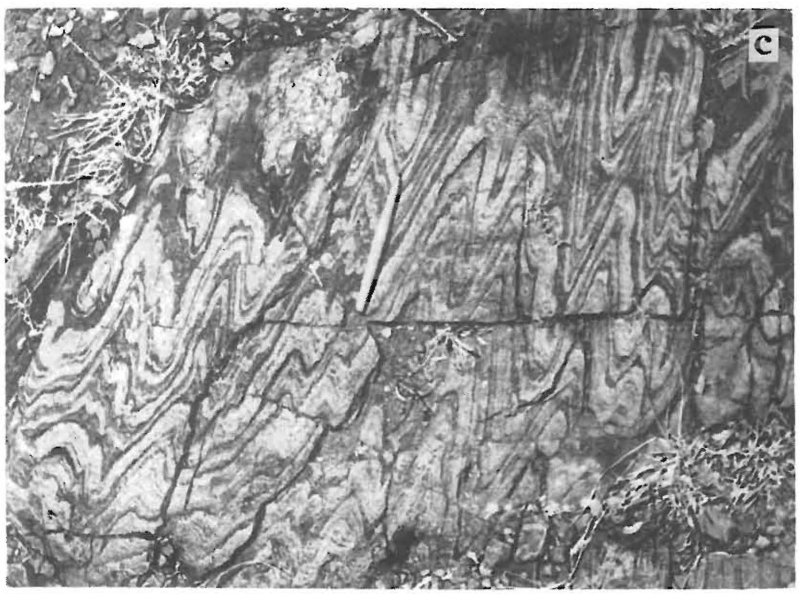
The second episode of basic igneous activity is represented by two-pyroxene granulites, cross cutting the interbedded amphibolite - sedimentary sequence (as at Hullahalli canal section (Plate I, Fig.'d') and as dykes cutting the ultramafic harzburgite-peridotite bodies as at Doddkanya.

Plate I. Ancient supracrustals (Sargur Type)



a. Broad folds in carbonate band, Bettadabidu.

b. Tightly folded manganiferous horizon, Terakanambi.



c. Banded magnetite quartzite showing complex fold patterns, Sargur.

d. Two generations of basic dyke, Hullahalli canal section. Note the folded younger two-pyroxene granulite body cutting the older amphibolite. The older amphibolite is interbedded with sillimanite schist/sillimanite-bearing paragneiss.

Relicts of ultramafic-gabbro-anorthosite (minor) complexes occur as discontinuous linear belts (see map/ Fig.2), pods in the gneiss and are later than the metasediments. Ultramafic complexes are characteristic units of this older Sargur assemblage. From field evidences it can be demonstrated that the ultramafic components are emplaced within the metasedimentary sequence as at Mavinahalli and Doddakanya. The significant feature of these units is that they show good mineral layering, igneous stratigraphy and occur interleaved with the gneisses. Good examples of chromite layering can be seen in Sinduvalli and Talur exposures. The chromites plot in the field of stratiform complexes.

Closer examination of chromite seams at Sindhuvalli have shown that even within the seams there is a gradation in grain size. Based on this chromite layering a "way-up" stratigraphy has been established for the Sinduvalli body (Srikantappa et. al., 1980). Even igneous stratigraphy to a certain extent can be discerned in the Doddakanya body. This body has a dunite/ harzburgite centre bordered by thin bands of bronzite peridotite which in turn is succeeded by pyroxenite. Thin bands of anorthositic gabbro are common. There is close interleaving of ultramafics and gneiss. Dunite is cut by dykes of two-pyroxene granulite. The garnet-bearing two-pyroxene granulite may represent original basalt or gabbro. The dunite/harzburgite is highly serpentinized and are hosts for magnesite deposits. Locally magnesite is being mined at Doddakanya for the last several years.

The other significant feature of the ultramafic component is that it has been subjected to later metamorphism of upper amphibolite facies. Metamorphic imprint can be seen in the form of orthopyroxene growth in between chromite seams as at Sinduvalli. Some of the chromites belong to ferrit chromite variety. Evidences of large scale recrystallization of these ultramafics to assemblages similar to sagvandites can be seen particularly along the border zones of the larger ultramafic bodies, as at Mavinahalli. These totally recrystallized ultramafics often occur as large sized boudins within the gneisses and the metasediments. The best example of this can be seen at Motha (Fig.2).

Quartzites bordering or adjacent to these ultramafic bodies often contain greenish paragonite, altered product of kyanite-sillimanite. Paragonite has appreciable Cr_2O_3 ($\simeq$ 1.3%). Evidently, chromium has been introduced into these rocks, from the ultramafics. This theory of Cr influx into the adjoining sediments can be applied only to cases of nearness and involvement of the various units in later deformation and metamorphism. Presence of fuchsite mica in the pelites and the derivation of chromium for the formation of fuchsite may be due to scavenging of Cr by the pelites, a primary feature of the sediments. Three major deformational episodes have been recognised (see map/Fig.2) (Janardhan et. al. 1979).

Pelites, the commonest litho units, are best exposed in the Sargur section. They are represented by kyanite-sillimanite $\pm$ corundum-graphite schists. Biotite-garnet schists and para gneisses with sparse sillimanite are also common. In pelites, kyanite show relics of staurolite. Kyanites-sillimanite transition is common. This indicates temperatures around 550-600°C and pressures of 5 Kb for the original Sargur metamorphism (prior to 3000 Ma gneiss emplacement). Higher temperatures of 750°C and pressures of 7-8 Kb reported by various workers (Srikantappa et al., 1985) represent the signatures of the superimposed granulite facies event around 2600 Ma.

The chemistry of the pelitic assemblages are given in Table-III. The pelites have significant zirconium and titanium content. Chemical plots (Janardhan et.al,1986) show that the pelites are normal sediments. Though Cr is abundant in the pelites, Ni is below average for Archaean sediments, showing an anomolous character. Abundant zircon and rutiles are often present in the kyanite - sillimanite schists as abundant accessories. Their presence goes against the view thatthe pelites may represent chemical precipitates. The Sargur assemblage, therefore, are normal sediments. The carbonate-Mn-horizon-BIF are true chemical precipitates. Thinness of beds and rapid alternation of the lithologies suggest their deposition in shallow continental marginal basins.

Carbonates occur prominently in the Bettadabidu, Terakanambi regions and are represented by calc-silicates and marbles. These are interbedded with older amphibolites, as at Bettadabidu. The carbonates consist of calcite-dolomite-diopside-hornblende-plagioclase (An_{70-80}) - serpentine-phlogopite-epidote/clinozoisite-sphene and graphite. Their chemistry (see Table III) indicates them to be of exhalative origin. Appreciable MnO (up to 7%) in the carbonates is significant. Abundant calc-silicate xenoliths can be seen in the gneisses of Gundlupet and Terakanambi.

One of the significant features of the Sargur assemblage is what has been loosely termed as the Mn-horizon. This band generally occurs in between carbonate and BIF lithologies. The Mn-horizon usually consists of spessartine-rich garnet-manganese-bearing pyroxenoids (MnO up to 9%) - rare orthopyroxene (MnO up to 3%)-quartz. The garnets have appreciable MnO content up to 23%. The MnO content of garnet, however, varies. Bulk chemistry of Mn-bearing rocks is given in Table-III. For garnet compositions, please see the paper of Janardhan, et.al.(1981).

Banded Iron Formations are common in Sargur Supracrustal assemblage. In the Sargur region, they have been used as marker horizons for identifying fold closures, as at

Kundapatna and Mullur. One of the smaller BIF bodies can be seen by the participants at Motha.

BIF are essentially quartz-magnetite bodies with cummingtonite/grunerite, altered orthopyroxene forming the main constituents. Garnet, hornblende and even biotite can be seen at places. These bands attain a maximum width of 50m. Apart from the association of other lithologies, very often these bands are interbedded with amphibolites representing original basalts. Association of Mn and to a lesser extent carbonate horizons are characteristic and significant. These BIF are different in character to that of Algoma and Superior types. The mineralogy, lithological associations and similarity of these bands to Salem (Kanjamalai) and Tiruvannamalai types had led Prasad et. al. (1982) to designate these Archaean BIF as a distinct type for which a special name Tamilnadu type has been proposed.

The chemistry of BIF is typical of chemical precipitates. Sargur BIF are characterized by low trace element contents (Table III). Positive Eu anamoly indicates oxygenic conditions. REE content is typical of Archaean BIF (Janardhan et.al, 1986).

Chemical data of amphibolites, metasediments and ultramafics are given in Tables II, III and IV.

Sargur type supracrustal rocks are not confined to the high-grade terrain alone. They are found as narrow strips and tectonic slices within the migmatite-gneiss all over the craton. A closer examination of the gneiss terrain is likely to reveal many more occurrences of such high grade lithologies. The name 'Ancient Supracrustals (Sargur type)' is best retained as a collective name to designate these various supracrustal sequences which represent remnants of the oldest volcanic and sedimentary rocks, fragmented and engulfed by later gneiss (Radhakrishna, 1983).

Table II Amphibolites

	24	5	7	1	760103	760110	195	GHI	184	125	177	183
SiO_2	46.90	48.41	48.77	49.08	52.77	46.89	44.81	47.71	48.70	48.96	50.99	54.98
TiO_2	2.05	0.97	0.72	0.73	1.54	0.68	0.73	0.75	0.56	2.60	1.68	0.24
Al_2O_3	12.37	15.09	14.18	14.44	13.40	17.06	15.57	14.11	15.05	12.15	13.30	13.51
Fe_2O_3	7.51	4.00	2.75	3.31			2.78	1.42	1.12	6.55	5.94	1.44
FeO	8.65	10.29	7.04	8.99	14.08	10.17	6.40	8.79	7.72	11.56	7.38	6.43
MnO	0.21	0.21	0.14	0.19	0.16	0.13	0.28	0.25	0.14	0.26	0.24	0.22
MgO	6.26	7.62	11.18	7.59	4.24	10.05	5.12	5.92	10.33	4.63	6.67	6.99
CaO	10.26	9.62	10.12	11.05	7.03	11.08	16.82	15.06	9.80	8.58	10.00	12.00
Na_2O	3.04	2.57	2.17	2.49	4.41	2.10	2.18	2.42	2.75	1.77	2.24	2.78
K_2O	0.30	0.32	0.33	0.23	0.85	0.35	0.17	0.17	0.68	0.68	1.00	0.43
P_2O_5	0.55	0.09	0.07	0.11	0.07	0.04	0.06	0.04	0.06	0.38	0.13	0.03
H_2O	0.51	1.30	2.60	1.88	-	-	1.38	0.98	2.01	1.04	1.10	1.10
CO_2	0.41	0.03	0.11	0.29	-	-	2.56	1.08	0.34	0.16	0.05	0.33
Total	99.10	100.52	100.18	100.16	-	-	98.86	98.70	99.26	99.32	100.72	100.48
Cr	171	231	792	213	96	778	284	224	324	90	174	753
Co	62	68	67	64	-	-	53	72	56	60	56	51
Ni	56	61	297	81	160	526	108	126	281	24	70	161
Cu	47	86	63	56	157	92	199	91	57	117	68	0
Zn	132	106	61	110	119	97	60	81	63	156	123	62
Ca	18	19	20	18	14	12	80	21	14	25	24	11
Rb	2	6	10	2	16	-	5	3	46	7	13	10
Sr	151	70	194	170	445	189	159	164	212	130	13	145
Y	43	29	10	18	38	18	16	12	11	61	28	9
Zr	169	77	70	90	183	43	58	52	71	196	104	37
Nb	6	2	9	6	25	4	1	4	5	8	5	8
Ba	70	54	56	40	330	65	33	51	79	76	81	90
La	14	6	7	17	43	-	0	1	2	6	4	2
Ce	46	28	19	30	107	39	36	31	27	37	27	13
Pb	3	7	5	7	-	-	8	-	1	6	10	3
Th	1	-	2	1	-	-	3	-	1	3	4	5

Explanation to Table-I

MODAL ANALYSES OF AMPHIBOLITES

24	Hullahalli:	Pl 45% + Hbl 15% + cpx 5% ± Zr ± Apa ± opaque
5	Manchanahalli:	Hbl 45% + pl 40% + cpx 10% Ca 5% + opx + Qz + opaque
7	Hunugalli:	Pl 45% + Hbl 30% + Bio 10% + Qz 10% + opx 5% + opaque
1	Kulya:	Act 50% Pl 35% + cpx 15% + Ga + Sph + opaque
GHI	Gundlupet:	Pl 25% + Hbl 40% + Diop 25% + Qtz 3% + Sphene + Scapolite
195	Honkarapura:	Pl 15% + Hbl 65% + Dio 15% + Scapolite + Sphene
184	Kurubarahundi:	Pl 35% + Hbl 60% + accessories
125	Gundlupet:	Pl 15% + Hbl 60% + Qz 10% + Ga 13%
177	Honkarapura	Pl 40% + Hbl 40% + Cpz 5% + epidote 4% + Qtz 8% + opaque
183	Kurubarahundi	Pl 40% + Hbl 35% + cpx 15% + Qz 5% + opaque

760103 and 760110-taken from Ph.D. thesis of Ramakrishnan M (1980), submitted I.I.Sc., Bangalore.

Table III Metasediments

	GM11	S132	S126	S180	BK150	BG1	GM3a	GM4	GH51	BO154	GH113	S140	S143	BK158
SiO_2	87.86	66.48	36.73	36.67	58.54	51.18	80.71	47.54	51.82	8.74	51.49	43.90	48.92	44.66
TiO_2	0.02	2.30	6.12	4.68	0.74	0.40	0.04	0.40	0.55	0.13	0.17	0.01	0.01	0.00
Al_2O_3	5.94	29.61	53.10	35.64	15.76	16.95	5.52	11.03	13.08	2.63	22.72	0.19	0.13	0.38
Fe_2O_3	0.07	0.06	0.17	6.05	2.12	0.76	1.73	2.83	13.23	1.15	5.60	49.48	44.18	37.55
FeO	0.17	0.03	0.10	10.90	9.14	13.61	0.48	4.83	1.19	3.86	0.89	2.50	2.89	11.81
MnO	0.02	-	-	0.13	0.17	0.17	6.96	17.60	14.22	0.98	0.24	0.08	0.09	0.07
MgO	0.42	0.20	0.36	1.93	4.72	8.95	0.62	3.59	2.60	1.38	0.79	2.02	2.41	0.95
CaO	0.29	0.07	0.70	1.24	2.35	1.18	1.87	6.69	2.19	46.38	13.30	0.81	1,05	0.56
Na_2O	2.50	-	0.94	0.75	2,25	1,09	0.27	0.19	2.25	0.25	0.65	0.01	0.01	0.24
K_2O	0.91	0.19	0.62	0.01	2.45	3.35	-	-	-	0.04	2.21	0.01	0.01	-
P_2O_5	0.01	0.06	0.06	0.05	0.13	0.16	0.01	0.08	0.07	0.03	0.05	0.07	0.06	0.06
H_2O	0.22	0.32	1.03	1.03	1.41	1.83	0.18	0.41	0.49	0.23	2.43	0.83	0.80	0.51
CO_2	0.11	0.13	0.05	0.13	0.60	-	0.24	0.46	0.06	34.56	0.40	0.21	0.09	0.11
Total	99.54	99.45	99.98	99.21	100.38	99.63	98.63	95.65	99.75	100.36	100.94	100.12	100.65	96.90
Cr	35	453	129	419	192	335	39	285	289	32	25	47	30	22
Co	0	7	9	55	38	68	3	57	34	13	10	11	14	15
Ni	7	-	9	1	71	188	12	46	54	8	3	-	-	5
Cu	17	23	31	1778	21	10	49	0	54	0	13	-	-	55
Zn	12	11	63	1128	99	74	29	120	65	10	44	-	-	21
Ga	3	48	99	66	29	15	4	15	6	6	69	11	12	13
Rb	11	5	11	3	109	63	3	3	3	4	185	2	4	7
Sr	49	2	68	79	164	41	18	29	19	48	1127	1	7	4
Y	0	130	44	110	25	26	10	37	21	2	15	4	-	6
Zr	51	513	966	538	124	ND	64	296	141	-	118	74	64	62
Nb	1	59	48	22	9	ND	3	11	10	-	2	3	6	91
Ba	175	115	314	160	320	298	37	49	214	-	214	14	15	49
La	2	54	55	24	15	-	0	20	9	17	9	26	9	0
Ce	7	1111	123	Ce-31	33	29	4	44	28	117	46	13	12	10
Pb	1	2	3	Pb 5	24	-	2	9	6	0	48	-	-	0
Th	1	29	15	7	12	-	4	21	14	1	12	5	6	5

EXPLANATION TO TABLE IV

GM	11	Quartzite, Kurubarahundi: Qz + Zr
S	132	Pelitic schist, Kulya: Qz 35% + Silli 35% + Kya 25% + Ru 5% + Zr + Opaque
S	126	Pelitic schist, Kulya: Qz 25% + Silli 40% + Kya 30% + Ru 5% + Zr + Opaque
S	180	Pelitic schist, Itna: Qz 5% + Felds 5% + Kya 30% + Silli 20% + Stau 10% + Ga 25% + Ru 5% + Zr
BK	150	Quartz-Biotite-Garnet Schist: Qz 30% + Pla 15% + Bio 20% + Ga 35%
BG1		
GM	3a	Manganiferous Quartzite, Madhalli: Qz 75% + Garnet 20% + 5% accessories
GM	4	Manganiferous Quartzite, Madnalli: Qz 30% + Diop 30% + Garnet 45% + Sph 2% + Opaque
GH	51	Manganiferous Quartzite, Gundlupet: Qz 55% + Garnet 40% + Cpx + Opaque
BO	154	Calc silicate: Calcite 80% + Hbl 10% + Cpx 5% + Sphene 2% + Garnet 3%
GH	113	Calc silicate, Honnashettihundi: Qz 55% + Diop 30% + Epidote 10% + Sphene 2%
		Scap 8% + Ziosite + Hbl + Garnet
S	140	BIF, Kulya: Qz 50% + Magn 40% + Opx/Cumm/Grun 5%
S	143	BIF, Kulya: Qz 60% + Magn 30% + Opx/Cumm/Grun 10%
BK	158	BIF, Kurubarahundi: Qz 60% + Magn 38% + Cumm/Grun

Table: IV

Chemical analyses of ultramafic rocks from the northern part of Sargur

	1	2	3	4	5	6	7	8
SiO_2	38.74	53.62	47.14	50.53	46.12	49.09	47.15	46.73
TiO_2	0.18	0.30	0.62	0.76	0.26	0.26	0.98	0.91
Al_2O_3	1.80	2.45	4.55	6.19	29.60	23.30	15.42	16.60
Fe_2O_3	4.77	1.07	0.87	1.91	0.85	1.52	2.58	0.53
FeO	3.66	8.76	12.90	8.23	1.41	3.40	7.92	8.54
MnO	0.16	0.22	0.25	0.45	0.10	0.05	0.06	0.08
MgO	39.90	28.17	23.59	16.24	3.65	6.66	12.63	12.00
CaO	0.90	2.76	6.17	12.37	13.20	8.80	7.80	9.00
Na_2O	0.22	0.46	0.51	0.44	5.04	5.06	4.20	3.94
K_2O	0.07	0.04	0.37	0.16	0.48	0.69	0.34	0.34
P_2O_5	0.02	0.22	0.05	0.08	-	-	-	-
CO_2	3.41	-	1.06	-	-	-	-	-
H_2O	5.37	1.24	1.57	2.53	0.25	0.13	0.35	0.06
Total:	99.20	99.31	99.65	99.89	100.96	98.96	99.43	98.73

1 = Average of 24 ultramafics (dominantly harzburgite); 2 = pyroxenite;
3 = Bronzite peridotite; 4 = Hornblendite; 5 = K 99 leuco-anorthosite;
6 - 8 = Gabbroic anorthosites.

Data from Janardhan et al (1978)

3. KOLAR SCHIST BELT

Geology

The Kolar Schist Belt, located 80 km east of Bangalore, is one of the eastern most, volcanic-dominated, auriferous belts in the Eastern Block of the Dharwar Craton (Viswanatha and Ramakrishnan, 1981). In the central part of the 80 km long belt active gold mining has been going on for well over hundred years.

The 3-4 km wide belt is divided into eastern and western parts, with respect to a central, fine-grained, ridge-like metavolcanic unit (Fig.3). The belt consists of two suites of tholeiitic and komatiitic rocks metamorphosed to lower-middle amphibolite facies (Rajamani et al, 1981). Tholeiites are the dominant rock-type in the belt. Banded iron formation and ferruginous quartzite occur as discontinuous ridges on the western margin of the belt and also as isolated lenses within the belt. In addition, the belt includes on its eastern margin, a unit of schistose felsic rocks known as the Champion Gneiss. This unit at places is agglomeratic with cobbles of granite, amphibolite and iron formation embedded in a fine grained felsic matrix.

Gold mineralization within the belt occurs as both stratiform-type sulfide lodes and vein-type quartz carbonate association. The latter type has significantly higher gold contents and is associated with the eastern amphibolites. The former type is banded, and occurs intercalated with iron formations within amphibolites (Sivasiddaiah and Rajamani, 1986).

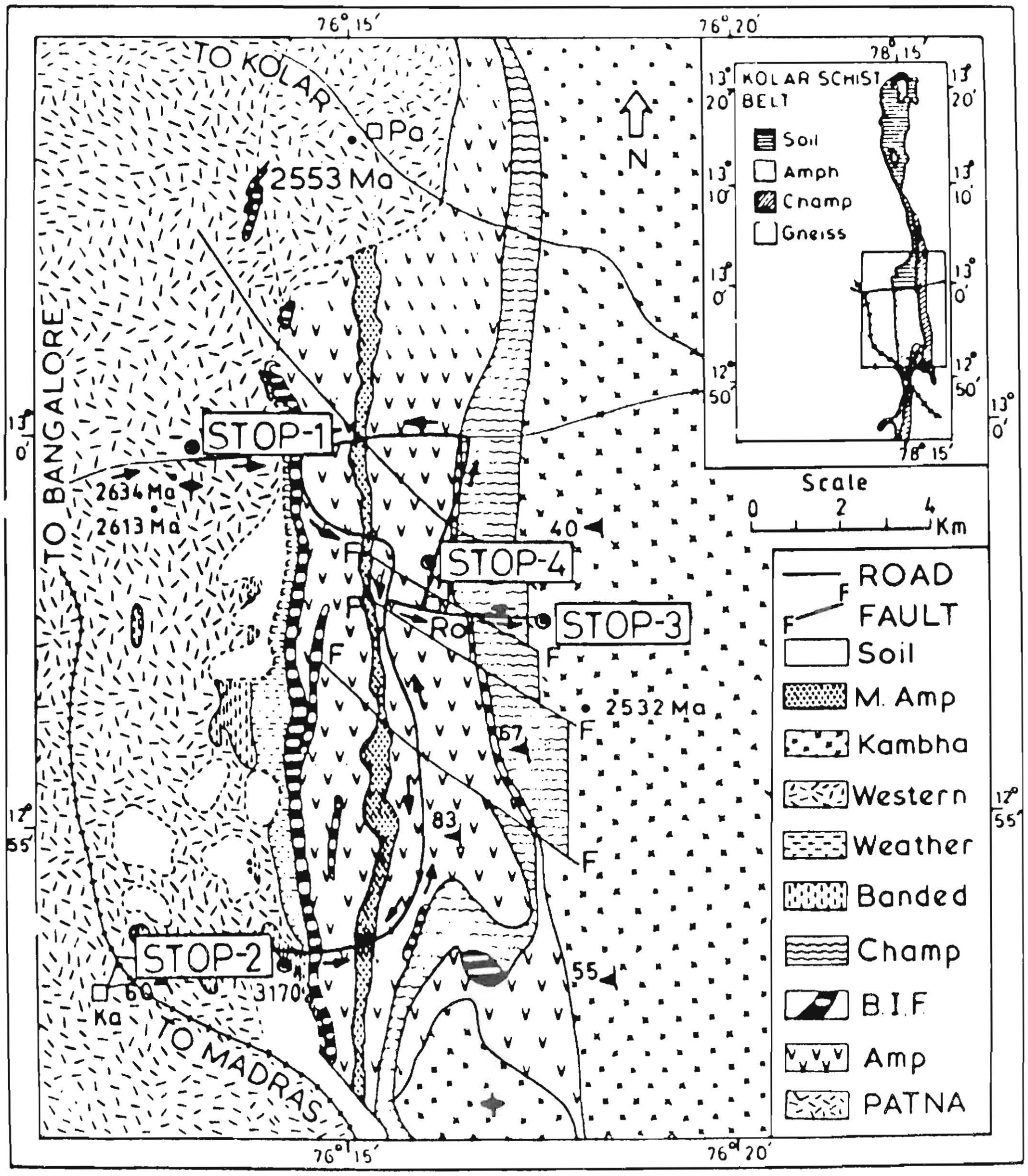


Figure 3 Geological map of the central Kolar Schist Belt. The heavy line indicates the route to be followed for the field conference with locations of four stops. Ages of major granitic gneisses are also indicated. Ka, Ro and Pa refer to Kamasamudram, Robertsonpet and Patna.

The belt is surrounded by granitic gneisses on both sides. The contacts between the gneisses and the schist belt are tectonic. The contact zones are highly sheared, locally mylonitized and are characterized by the development of quartz muscovite schists from orthogneisses on the west.

The gneisses on the west have four major components in addition to several generations of felsic dykes and pegmatites. The major components are the Dod Gneiss, Dosa Gneiss, the Patna Granite and the Banded Gneiss. On the east the gneisses are relatively homogeneous in composition and are referred to as the Kambha Gneiss.

Structure

Rocks of the belt have been subjected to at least three phases of folding and to a late-stage, ductile shearing events (Mukhopadhyay et al 1987). The amphibolites have well developed schistosity generally striking N-S and dipping subvertically. The first two generations of tight isoclinal and recumbent folds and late-stage ductile shearing are related to an E-W subhorizontal compression. F_3 folds which resulted in dome-and-basin interference patterns are a result of longitudinal shortening during the waning phase of the folding episodes. Gneisses on both sides have foliation and secondary layering that are parallel to the N-S foliation of the belt. The foliations on the western gneisses dip at high angles ($>$ 60°) to the east with shallow north or south plunging lineations. The eastern gneisses have foliations striking N 10° $\pm$ 10°E and dipping 60° to 80° to the west. Most of the earlier structures present in the gneisses have been transposed parallel to the N-S trending ductile shear planes.

Amphibolites

Within the belt, amphibolites are the major rock type. There are two suites of komatiitic and tholeiitic amphibolites. The west-central komatiitic suite has a maximum of MgO content of 23 wt per cent (hydrous basis) and has variable REE patterns (Fig.4). Their chemistry suggests that they were derived by different, but low ($<10\%$) extents of melting of LREE depleted mantle sources leaving garnet in the residue from depths greater than 100 km (Rajamani et al 1985). This melting resulted in variable Sm/Nd ratios for the west-central komatiites which yield a Nd whole isochron age of 2690 ± 140 Ma. A unit of west-central tholeiitic yielded a Pb-Pb isochron age of 2733 ± 155 Ma (Balakrishna et al 1987). The tholeiites have come from much shallower (~ 30 km) mantle sources, which are geochemically distinct from those of the komatiites(Rajamani -(submitted)).

Both komatiitic and tholeiitic suite of amphibolites on the eastern part of the belt have higher abundances of LILE and light REE enriched patterns (Fig.4). Their sources however had a long-term LREE depleted histories but with a long term U/Pb ratio higher than those of the western amphibolites.

The Champion Gneiss

The composition of the clast-free Champion Gneiss varies from dacite to rhyolite. The dacitic type has major and trace element chemistry, including REE patterns, similar to those of the Dod Gneiss on the west side (Fig.4; Table V).

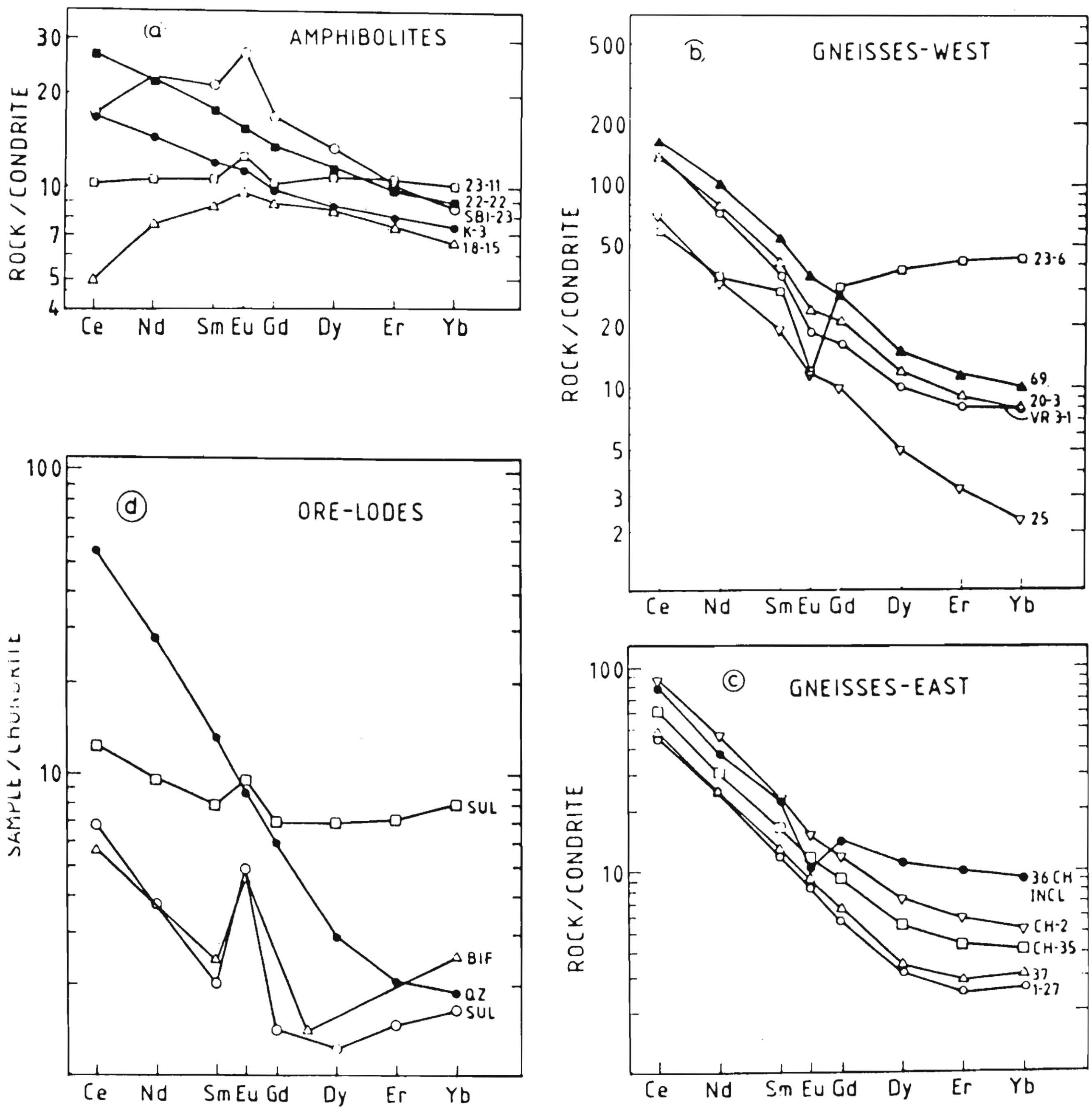


Figure 4. Chondrite normalized REE patterns of major rock types and ores in and around the Kolar Schist Belt. Numbers adjacent to patterns in a, b and c refer to those in Table I.

Zircons from a granite cobble yielded a minimum U-Pb age of 2900 Ma. A pyroclastic origin has been proposed for the Champion Gneiss with conglomerates (Ziauddin 1975). If the magmas for the Champion Gneiss were mantle derived, which seems likely, then the mantle sources for these magmas must have undergone significant enrichment in LILE (Balakrishnan and Rajamani, 1987).

Iron formation

Banded iron formation is intercalated with amphibolites and graphitic schists on the western margin of the central part of the schist belt. Iron minerals are much less abundant than quartz and the average iron content is about 12 wt% (Behera and Rajamani, 1985). The iron minerals include grunerite, pyrrhotite, magnetite$\pm$Fe carbonate. Grunerite and magnetite often appear to be metamorphic products of iron carbonate. Proportions of iron minerals are quite variable. There is no regular, discernible mineralogical facies. They have very low abundances of Al_2O_3, base metals and REE (Fig.4). The deposition of the iron formation seems to have been related to submarine volcanic exhalative processes (Behera and Rajamani, 1985).

Gold mineralization

Gold mineralization occurs throughout the central and southern part of the schist belt. There are major differences in the association, structures, mineralogy, geochemistry and gold tenor between the lode-type and vein-type mineralization. The latter type is present only on the eastern part of the schist belt associated with LREE-enriched amphibolites. The lode-type occurs throughout the schist belt, as discontinuous lodes often associated with cherty iron formations. The lodes have variable sulfide, magnetite, basemetals and gold contents. The sulfides are dominantly pyrrhotite and arsenopyrite. The proportions of the latter are quite variable and have no relation to gold contents. In the central part, the Kolar Gold Fields area, there are at least three major parallel sulfide lodes (West Prospect, Oriental and Mac Taggert) which show regular geochemical and mineralogical variations from west to east. The Champion Reef, a vein type deposit occurring further to the east of these sulfide lodes, has been mined to a depth greater than 11000 feet because of its high gold tenor (>10 ppm). These quartz-carbonate rich veins have also unusually higher concentrations of Cr and Ni, a feature requiring a very reduced condition of metal transport, perhaps in the form of carbonyl complexes. The lode-type could have a volcanic exhalative origin whereas the vein-type mineralization has been a result of multistage gold enrichment processes associated with metamorphism, deformation and even magmatic intrusions (Sivasiddiah and Rajamani 1986).

W. Gneisses

The gneisses on the west side of the schist belt are very heterogeneous, range in composition from monzodiorite to granite and in age from at least 3200 to 2550 Ma (Krogstad et al, 1986). The monozodioritic to granodioritic gneiss, referred to as the Dod Gneiss (2632 Ma) has major and trace element compositions, including REE patterns that are similar to mantle-derived sanukitoid rocks described in (Shirey and Hanson, 1984). The Dosa Gneiss (2613 Ma) and the Patna Granite (2553 Ma) are granodioritic to granitic and have compositions that could be related to mantle-derived sanukitoid type magmas by fractionation processes including liquid immiscibility. A crustal origin for this suite of plutonic rocks is ruled out (Balakrishnan and Rajamani, 1987). However, their Pb, Nd and Sr data on whole rock samples and Pb data on K-feldspar indicate variable extents of contamination of their magmas by a significantly older (> 3200 Ma) crust (Fig.5) (Krogstad et al, 1987). The existence of an older basement is also indicated by the presence of inherited zircons in some of these plutons and also by the presence of the granitic Banded Gneiss which has an evolved major and trace element and isotopic composition as well as zircons which are at least 3200 Ma. The Dod and Dosa gneisses were metamorphosed to amphibolite facies between 2632 and 2553 Ma ago and were affected by ductile shearing before 2420 Ma.

E. Gneisses

The granodioritic to granitic Kambha Gneiss (2532 Ma) which includes the Bisanattam Granite (Narayanaswami et al, 1960) is geochemically and isotopically very homogeneous (Rajamani et al, 1987). Just 2 km east of the contact zone, the gneiss has relatively more leucocratic "blebby" zones with megacrysts of amphibole (after orthopyroxene?) and

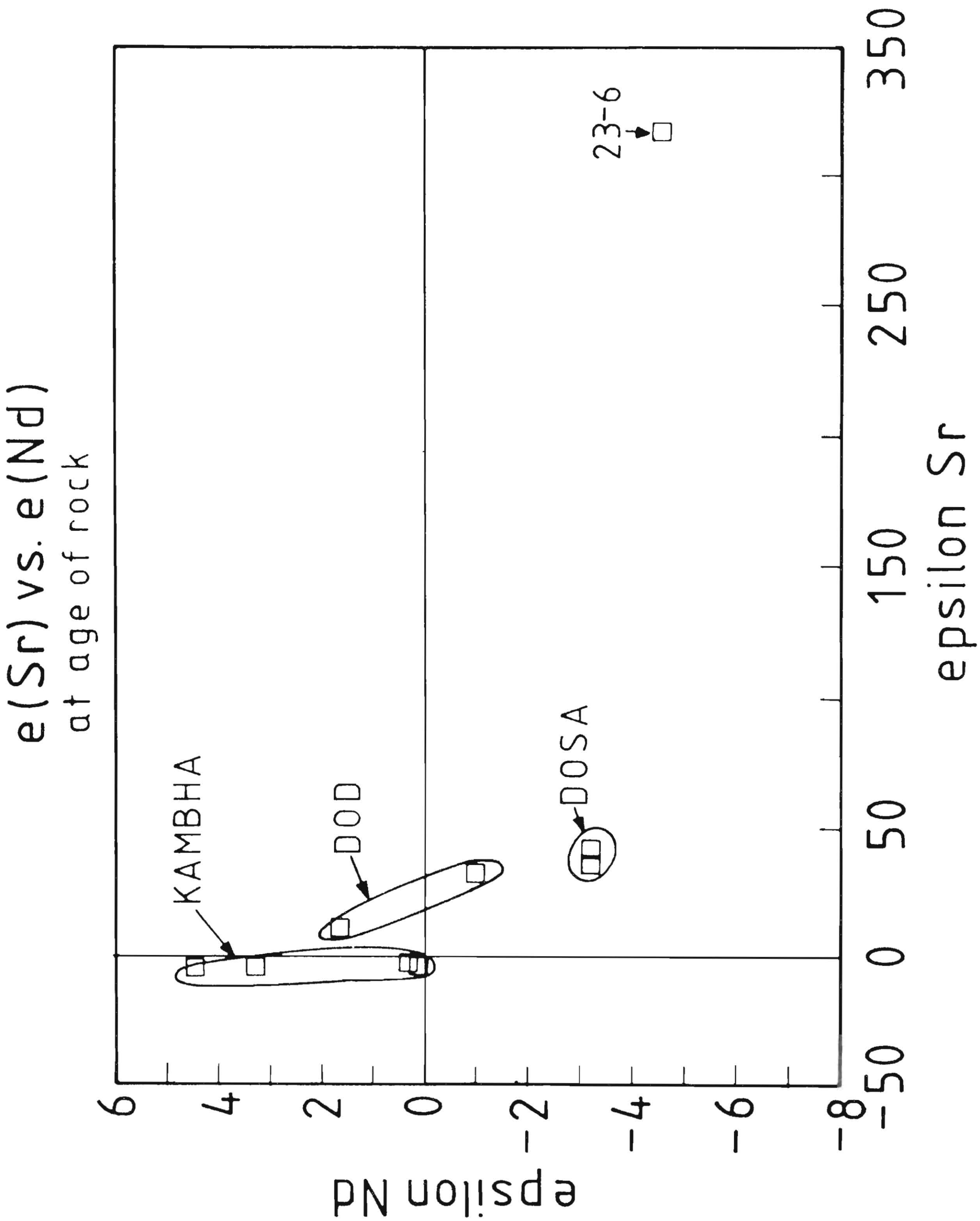


Figure 5. Epsilon Sr versus epsilon Nd diagram for the major granitic gneisses around the belt. Note the difference between the Kambha and Dosa gneisses present on the east and the west side of the belt respectively, which are otherwise similar in their elemental abundances.

sphene and becomes agmatitic locally. A crustal origin for this 2532 Ma old granodioritic gneisses is unlikely (Balakrishnan and Rajamani 1987; Krogstad et al 1987). Their Nd, Sr and Pb data suggest a derivation from mantle-like sources. Their magmas were not contaminated by any significantly older crust. The gneiss was cooled from granulite to amphibolite grade before 2521 Ma and underwent rehomogenization of Pb on the hand specimen scale around 2400 Ma, probably due to fluid movement during shearing.

Tectonic model

Within the west central part of the Kolar Schist Belt, komatiitic and tholeiitic amphibolites occur which were derived from depleted, MORB-type mantle sources with different U-Pb histories. The eastern suite of amphibolites were derived from long-term depleted, but short-term enriched mantle sources with higher U/Pb histories. Thus, mafic rocks formed from distinct mantle sources, representing different tectonic settings in terms of modern plate-tectonic analogues are present within 3-4 km wide schist belt with certain geographic assymmetry.

Continental crustal rocks, with distinct geological histories, occur on either side of the belt. The gneisses on the west side of the belt were formed between 2630 Ma and 2550 Ma ago; their magmas were contaminated by at least 3200 Ma old continental basement; cooled from amphibolite facies P-T conditions before 2553 Ma. The gneisses to the east were formed around 2530 Ma ago; their magmas were not contaminated by any significantly older crust; were cooled from relatively higher metamorphic P-T condition before 2521 Ma. These age differences between the western and eastern gneisses imply that these two gneiss terranes were not in close proximity to each other before 2521 Ma. Their isotopic differences suggest that the magmas for the two gneiss terranes were emplaced in completely different tectonic settings. Thus the Kolar area is a collage of at least four different terranes (Fig.6). The schist belt itself separates two discrete continental terranes and is therefore considered an Archaean Suture (Hanson et al,1986).

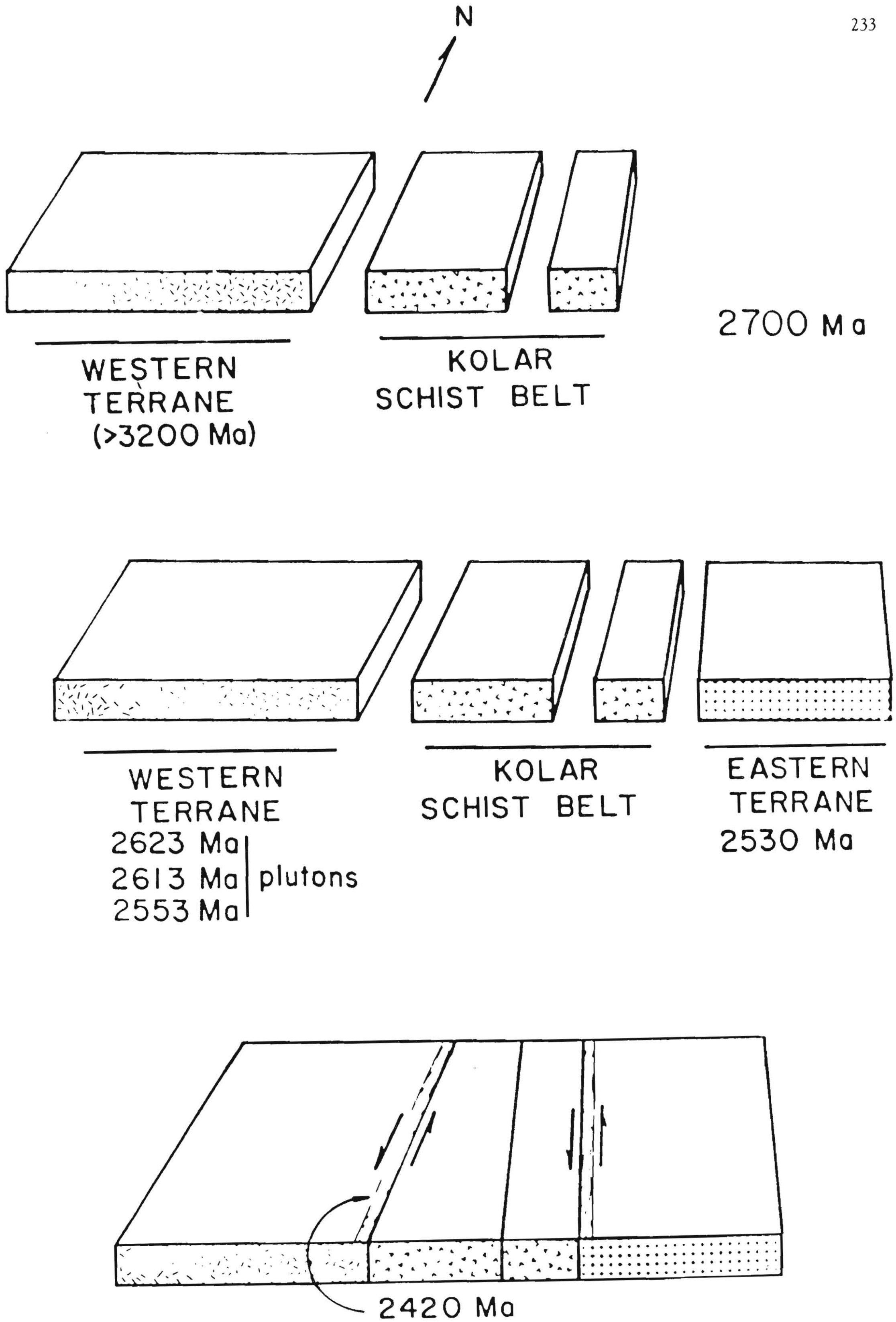


Figure 6. A possible model for the tectonic evolution of the area around the Kolar Schist Belt near Kolar Gold Fields. 2700 Ma is the age of the amphibolites present within the belt (5). Note what is now the eastern terrane did not exist prior to 2530 Ma.

Table 5. Composition of Kolar amphibolites and Gneisses

Sample No.	Amphibolites					Gneisses						
	Kom - West		Thol-West	Kom-East	Thol-East	Dod		Dosa	Band Gn	Champ	Kambha	
	18-15	SB1-23	23-11	K-3	22-22	69	20-3	25	23-6	CH2	VR1-27	E84-37
SiO_2	45.75	43.02	53.53	45.10	53.84	60.91	64.69	71.51	73.36	63.90	71.30	74.30
TiO_2	0.73	1.70	0.89	0.81	1.15	0.68	0.49	0.25	0.09	0.50	0.20	0.21
Al_2O_3	8.85	9.67	15.76	11.87	14.15	16.84	14.48	14.71	13.25	14.11	14.75	14.73
FeO(T)	12.97	15.67	9.30	11.90	9.86	5.71	4.34	1.75	1.58	5.10	2.23	1.50
MnO	0.19	0.26	0.24	0.22	0.24	0.10	0.09	0.03	0.04	0.15	0.05	0.04
MgO	21.34	15.88	6.56	15.75	5.51	3.92	2.97	0.73	0.19	2.86	0.56	0.68
CaO	8.62	11.10	12.81	11.20	13.95	5.71	3.70	1.85	1.21	7.55	2.33	2.35
Na_2O	0.04	0.75	0.86	1.31	0.38	4.62	3.91	3.90	3.87	2.66	4.75	4.91
K_2O	0.00	0.04	0.05	0.70	0.12	1.76	2.79	3.93	4.17	2.50	2.75	2.67
Mg.No	0.75	0.65	0.56	0.70	0.50	0.59	0.55	0.47	0.18	0.50	0.35	0.46
Cr	3028	1850	210	1347	1019	152	100	-	-	240	10	9
Ni	1048	1058	109	378	112	63	72	-	-	122	4	2
Zr	37	103	47	66	93	215	150	109	111	128	70	100
Rb	-	-	1	12	4	90	87	116	118	60	110	99
Sr	17	84	138	214	116	835	574	290	144	388	522	536
Ba	-	-	139	106	56	883	819	679	630	680	1102	650

4. PENINSULAR GNEISS COMPLEX

Over 80% of the granite-greenstone terrain is made up of grey gneisses and their modifications for which the name Peninsular Gneiss has been given. It represents a complex of migmatitic gneisses believed to be the result of influx of tonalitic, trondhjemitic and granodioritic material into the crust on an extensive scale around 3000 Ma ago. They are essentially orthogneisses with low initial strontium isotope ratios (Radhakrishna, 1974; Swami Nath and Ramakrishnan, 1981, p.81). This event corresponds to the chelogenic or shield forming cycle of Sutton (1963), the pantectogenesis of Swami Nath et al. (1976), the continental accretion differentiation superevent (CADS) of Moorbath (1977, 1978) and has helped to differentiate the greenstone sequences into two distinct groups—Older Greenstones which are greatly affected by the pervasive invasion and migmatisation by gneisses and Younger Greenstones in which basement-cover relations are clear and the greenstones rest on a gneissic basement with a clearly recognisable unconformity (Radhakrishna, 1976).

Inclusions within the gneiss are mainly mafic and ultramafic and can be of any dimension ranging from fragments to schist belts. All gradations in the transformation of older schists, through augen gneisses, granodiorites and granites can be observed. Polyphase deformation is characteristic of the gneissic region as a whole. Since the oldest gneisses carry relics of pre-existing mafic and ultramafic sequences, it is argued that the earliest crust was mafic and oceanic in character. The identification of relict Archaean oceanic crust, however, has remained as one of the most interesting unresolved problems of Precambrian geology (Bickle et al 1975).

Migmatites are interpreted to be the result of injection of tonalitic-trondhjematic material into preexisting mafic and ultramafic greenstones and granitization of greenstone sediments. Younger potash granites are ascribed to be the result of anatectic fusion of older tonalitic and trondhjematic material.

Taylor et al., (1984) have pointed out the U-Pb relation in these suites from Karnataka are in marked contrast with the commonly severe U depletion and consequently unradiogenic isotopic composition observed in deeply eroded, high-grade Archaean gneiss terranes. From this evidence they infer that the cratonic rocks of central Karnataka represent a relatively high level in the original Archaean continental crust.

Field relation and geology must decide on the relative ages of greenstones and gneisses. Sm-Nd isotopic ages are expected to prove useful in determining the ages of older greenstones.

There is no compelling reason to continue the names 'Dharwar' and 'Peninsular Gneiss', however entrenched in geological nomenclature they may be, to represent all the schistose and all the gneissose rocks of the Indian Peninsula and desist from attempts at further classification. Within the Peninsular gneisses alone three distinct events around 3400, 3000 and 2600 Ma have been recognised. 'Basement gneiss-overlying volcano-sedimentary accumulations— diapiric plutons', form a cycle and it should become possible to recognise several such cycles which have helped in the growth and stabilisation of the Archaean crust.

Future field work should obviously aim at distinguishing the individual cycles which have helped in building the Archaean crust (Radhakrishna 1983).

5. CLOSEPET GRANITE

A striking feature of the geology of the granite-greenstone terrain is the occurrence of a long linear belt of younger potassic granites extending in an arcuate manner for a length of nearly 500 km and having the same physiographic trend as the major greenstone belts. This granite belt is not a single mass of granite as represented, but consists of multiple intrusions emplaced within the Peninsular gneiss complex. The most characteristic rock type belonging to this younger granitic episode is a coarse-grained porphyritic potassic granite with large-sized porphyroblasts of grey or pink-coloured microcline. The porphyroblastic character of the feldspars is considered to be the effect of potash metasomatism through influx of late stage potash-rich solutions along a belt of weakness in the crust (Radhakrishna, 1956). Enclaves of older gneisses are present within the granite.

From the modern view point of plate tectonics, it is possible to conceive of the development of potassic granite plutons along collision belts of adjacent plates. Eventually, palaeomagnetic pole analysis should be able to test this possibility. It is interesting to recall the view of Swami Nath et al (1976) that this younger granite belt represents a major geo-suture demarcating the granite-greenstone terrain into two distinct blocks of differing crustal thickness. Seismic evidence also suggests a discontinuity (Kaila et al 1979).

Friend (1981) who has recently examined the southern continuation of the granite has confirmed development of megacrysts of potash feldspar in response to activity of late stage K-rich fluids in a still active stress zone. He has also agreed with the conclusion that the Closepet granite is the result of process of anatexis and partial melting of Peninsular gneisses. He connects the development of charnockite patches (as seen at Kabbaldurga) with the development of Closepet granites, both events being contemporaneous. Charnockite formation as a result of an influx of mantle derived volatile phase rich in CO_2, according to him, would drive out H_2O released from the hydrous minerals like biotite and amphibole, which in turn, would result in crustal fusion and generation of granite magma. He is of the view thatthe area lying at the southern margin of the granite-greenstone terrain is fundamental to the understanding of the processes of both charnockite formation and granite formation deep in the crust.

6. GEOLOGY OF THE SOUTHERN EXTENSION OF CLOSEPET GRANITE

The Archaean ($\simeq$ 2500 Ma) Closepet granite is a polyphase body intruding the Peninsular gneiss complex and associated supracrustal rocks. The granite outcrop runs for nearly 500 Km along N-S direction from Kabbaldurga in the south and up to Deccan plateau in the north and cuts across the regional metamorphic structure. In the amphibolite-granulite facies transition zone the granite displays complex internal structure, where it is intimately mixed with migmatites and charnockite. Field observations suggest that anatexis of amphibolite facies Peninsular gneisses has led to the formation of granite melt and there is a space-time relationship between migmatite formation, charnockite development and production and emplacement of granite magma. A distinct melting zone is recognised along the margins of granite outcrop, where one can observe all stages of granite formation, i.e., from migmatite formation to production and accumulation of granite melt into individual phases. Additionally the granite body is bounded by discontinuous outcrops of high grade supracrustal rocks, which bear significance to the granite emplacement, as immediately outside these supracrustal units, the amount of melting diminishes, thus, they may have acted like walls in checking the granite activity.

Based on the mode of occurrence, texture and cross cutting relationships four major granite phases are recognised. The chronological sequence of emplacement of major granite phases is as follows:

1. Pyroxene bearing dark grey granite.
2. Porphyritic granite.
3. Equigranular grey granite.
4. Equigranular pink granite.

The dark grey granite is the earliest recognised member of the granite body suite, generally occurs as discontinuous sheets and boulder strewn outcrops along the margins of the porphyritic granite. They are foliated due to the allignment of mafic minerals.

The porphyritic granite is megacrystic and form the most voluminous phase occurring as high hills and inselbergs. The porphyritic granite shows pronounced foliation in NNE direction, which is largely defined by the alignment of K-feldspar megacrysts. Based on the colour of the megacrysts, two varieties are recognised viz., porphyritic pink and porphyritic grey granite the porphyritic grey granite being found invariably fringing the porphyritic pink granite.

The equigranular grey granite commonly occurs as sheets, predominantly along the margins. Occasionally the grey granite contains agmatitic basic bodies.

The equigranular pink granite occurs as sheets and anostomosing network of cross cutting veins. In some instances the pink granite is garnetiferous and contains garnet amphibolite xenoliths.

242 A number of pegmatite and rare aplite veins recognised out across all the major granite phases.

Additionally there are small areas of K and Na rich rocks such as brick red rocks (9.7% K_2O) and albitite (11.6% Na_2O). Field and geochemical features suggest they could have arisen by extensive metasomatism.

Closepet granite and charnockite relations:

Rama Rao (1945) very early recognised that there is a close relation between charnockites and Closepet granites - the group of young potassic granites fringing the Archaean granite-greenstone nucleus (See Radhakrishna and Naqvi, 1986). Age data (Venkatasubramanyam, 1975) have tended to confirm this inference. Field evidences indicate that formation of charnockites and Closepet granite was very nearly contemporaneous (Janardhan et.al, 1982). Friend (1983) has demonstrated that the generation of granitic melts by partial anatexis of Peninsular gneiss components and their emplacement is co-eval with the formation of charnockite. A genetic link between the Closepet granites and charnockite event has been suggested (Friend, 1983). Geochemical aspects of origin of Closepet granite is examined by Allen et. al. (1986), who also have come to similar conclusions.

The fact that Closepet granite occurs in a N-S linear belt far away from charnockite is not explained fully by the above concept. The tectonic significance of the seggregation of granite diapirs all along the border of the older Karnataka nucleus has to be elucidated. A suggestion has been put forward (Radhakrishna and Naqvi, 1986) that this is due to basement activation on an extensive scale as a result of collision leading to crustal thickening, melting and high level emplacement of potassic granite, in the same way as proposed by Dewey and Burke (1973). Continental collision is viewed as an important probable factor in widespread basement reactivation leading to the production of charnockite as well as potash granitic plutons.

7. GRANULITE FACIES ROCKS - CHARNOCKITES

In the strictest usage, charnockite is an orthopyroxene-bearing granite with or without garnet (Holland, 1900; Subramaniam, 1967). However, among Indian geologists, the usage is extended to include orthopyroxene-bearing rocks ranging in composition from tonalitic to granitic gneisses, and also basic igneous enclaves within the gneisses. The present usage of terms like basic, intermediate and acid charnockite, though after Holland (1900) is not in the sense of an igneous series. The term 'charnockitic terrain' is also often used more in the sense of a granulite facies terrain.

The highest grade rocks in southern Karnataka and regions further south, tend to form hilly terrains, like those of the Biligirirangan, Nilgiri and Coorg. Due to chlorite veins lacing quartz and feldspars in charnockites, they look nearly as dark as the mafic grains, giving the rock a dark, massive appearance. On closer inspection, however, and on weathered surfaces, these dark greasy charnockites exhibit structures, in no way different from the amphibolite facies gneisses. They contain bands, lenses and schlieren of basic rocks, which except for their higher metamorphic grade, are similar to the metabasic enclaves in the lower grade gneisses. They exhibit migmatitic structures. Bands of BIF, Mn-garnet-bearing horizons and pelitic horizons too are not uncommon in the high charnockite hill ranges, (cf. Biligirirangan Hills, Rama Rao, 1945; Coorg ranges, Gopalakrishna et.al. 1986). These features, together, suggest that the charnockite terrain is basically a more intensely metamorphosed equivalent of the amphibolite facies terrain of the north.

The most striking features about the gross metamorphic pattern in Karnataka State is a southward increase in the metamorphic grade (Pichamuthu, 1965); thus, there is a southward increase in the depth of exposure, making it possible to examine a vertical cross section of the granulite facies terrain commencing from moderate pressures (5.5 kbs) as at Kabbal, to high pressure charnockites ($\sim$ 10 Kbs) at Nilgiris.

The abundance of granulite facies rocks in the deep crustal section of the Indian shield and that of other Precambrian shields lead to the inference that the lower continental crust is likely to be made up largely of granulitic rocks. The dense minerals pyroxene and garnet of these quartzo-feldspathic granulites, impart elevated densities and seismic velocities, appropriate of the lower crust (Smithson and Brown, 1977). One of the most important problems of modern geology is that of finding out what processes had operated in this inaccessible deeper crust to produce these characteristic group of rocks. The mechanism of granulite formation is a matter of vigorous current debate.

It is now known that granulites are the products of metamorphic episodes at specific periods of time ($\simeq$ 2600 Ma, 1000 Ma; and 640 Ma) that operated on limited portions of the earth's crust. Metamorphic PT Regimes (generally of 8-9 Kb) indicate anamolous crustal thickening and heating episodes, different from the ambient Precambrian geotherms. Rocks of terrestrial origin (supracrustals) have got buried to depths of 30 Km or slightly more, corresponding to the base of normal continental crust.

The significant thing is that the mineral assemblages typical of peak metamorphism were effectively frozen at some stage and are still preserved even after uplift.

Most workers now agree that granulite facies mineral assemblages formed at reduced water activity, and at temperatures well above hydrous melting in normal lithologies. The definitive mineral orthopyroxene formed at water pressures, near the lower stability limits of its hydrous precursors hornblende and biotite (Phillips, 1980). Fluid inclusions tend to be CO_2-rich and H_2O-poor in these rocks (Touret, 1981).

The following are the major mechanisms which have been suggested for the formation of granulites through dessication of precursor rocks:

1. Partial melting with absortpion of H_2O into anatectic melts, leaving behind a dry residue (Fyfe, 1973; or a modification of the same, "rock dominated metamorphism" (Fyfe, 1978).

2. Dilution of initial H_2O with CO_2. This process was involved for sub-solidus conversion of amphibolite facies gneiss to charnockite by Janardhan et. al., (1979, 1982); Condie et al, (1982) and Lamb et. al., (1986). Sources of CO_2 may have been deepcrustal, as from deeply (and/or swiftly) burried sediments (Glassley, 1983; Drury et. al., 1984) or subcrustal as in outgrassing of a carbonated mantle (Sheraton et. al., 1973), or as a crystallizing gabbroic or basaltic underplate (Touret, 1971; Harris et. al. 1982), or intermediate mid-crustal intrusion (Wells, 1979).

3. By dehydration of rocks under fluid-absent conditions (Thompson, 1984).

4. Granulite formation by a sudden decrease of fluid pressure (Srikantappa et. al., 1985). This model envisages escaping of pore fluids along shear systems when the system changed from ductile to brittle.

5. Baking out of rocks in shallow contact aureoles prior to high pressure metamorphism, as seen in the Adirondocks (Valley and O'Neil, 1984).

8. HIGH PRESSURE CHARNOCKITES OF NILGIRI HILLS

Introduction

The massive charnockites of the Nilgiri Hills (Ooty) occupy the highest plateau (△ 2694 metres above MSL) in southern India. The general view of Indian geologists is that the charnockites of Nilgiris represent the deep crust and that the Nilgiri block was uplifted and juxtaposed against the amphibolite facies terrain. Deep seated faults or shears like the Moyar-Bhavani and Noyil-Cauvery bounding this block (see Fig.7) and ubiquitous pseudotachylites are often quoted as evidences for this uplift (Radhakrishna, 1968; Narayanaswamy, 1975).

The Moyar lineament is a major geological feature. It separates the Biligirangan Hills from the Nilgiri. The lineament itself is 200 km long and 20 km wide. NS fabric of the Sargur and BR Hills terrain swings to N 60°E in the vicinity of Moyar and to EW within the Moyar shear zone. A dextral shift of almost 80 km has been indicated (Drury and Holt, 1980). The Moyar shear is considered to be of Proterozoic age separating the BR Hills and Nilgiri charnockitic massifs.

The other major lineament - the Bhavani lineament occurs on the southern margins of the Nilgiri and extends eastwards into the plains. This lineament was considered as a reactivated older lineament. It hosts the layered anorthosite complexes of Bhavani and Sittampundi of Archaean age (Selvan, 1982).

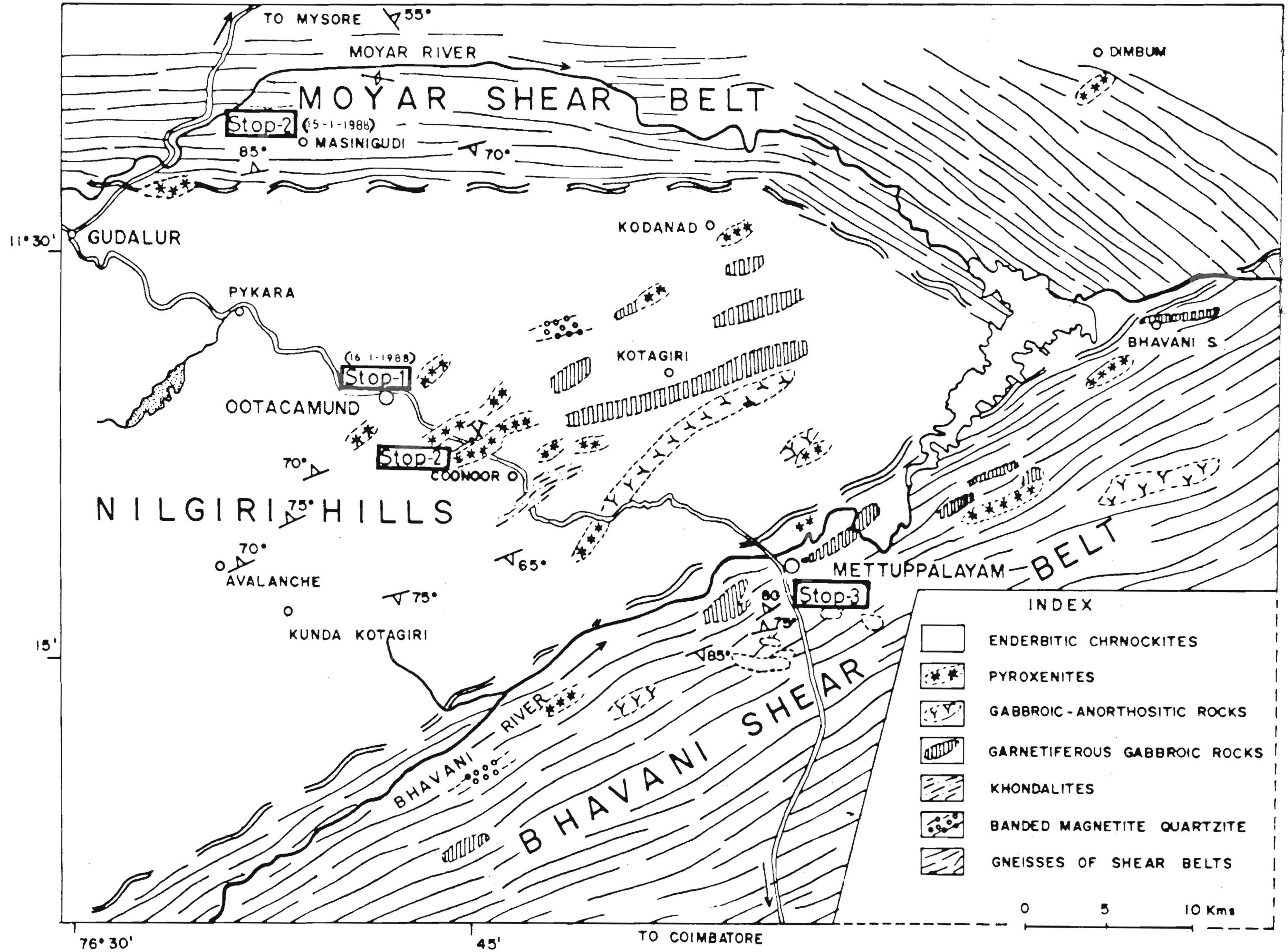


Fig.7 GEOLOGICAL MAP OF NILGIRI HILLS (after Srikantappa et.al., 1986)

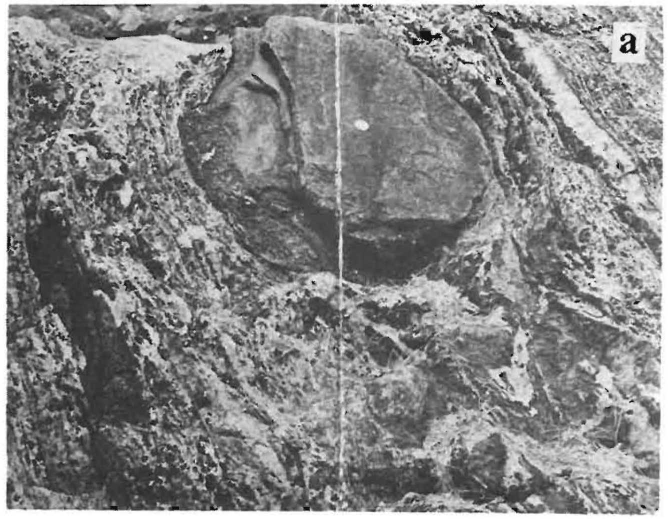
Charnockites

The granulite terrain of the Nilgiri Hills is predominantly composed of dark, greenish-grey charnockite with isolated bands and lenses of various metasedimentary units like garnet-biotite-feldspar-sillimanite/kyanite-quartz gneiss, banded magnetite quartzite ($\pm$ garnet $\pm$ hypersthene) and quartzite. Similarities in the lithologic composition of the Nilgiri charnockite terrane and the Bhavani shear belt suggest that the two are one and the same (Srikantappa, et. al., 1986).

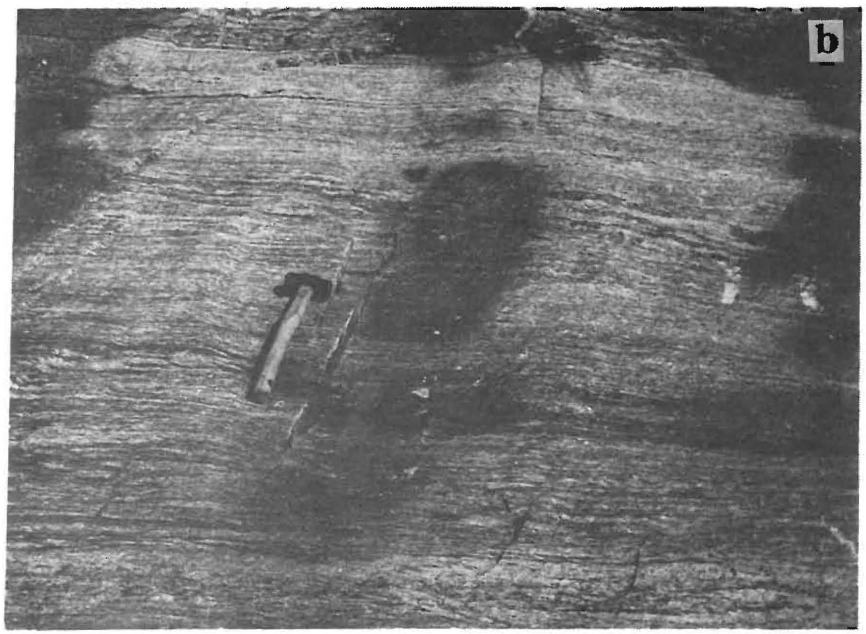
Charnockites are generally coarse-grained. Tight, minor isoclinal folds are observed and the rocks exhibit good foliation defined by alternate bands of garnet-orthopyroxene-biotite rich zones with feldspar and quartz-rich layers. The foliation trends N 60-70°E with steep dips. The general greasy appearance of charnockite is a major hindrance to observation of structures.

There are both non-garnetiferous and garnetiferous charnockite in the area with the latter dominating the Nilgiri massif. The granoblastic polygonal microtexture of the charnockite demonstrates thorough recrystallization under high P-T conditions. During the development of the Moyar and Bhavani shear belts, however, the charnockite massif has been dissected by several shear zones. This has led to the development of flaser and mylonitic textures in the charnockites without affecting the granulite

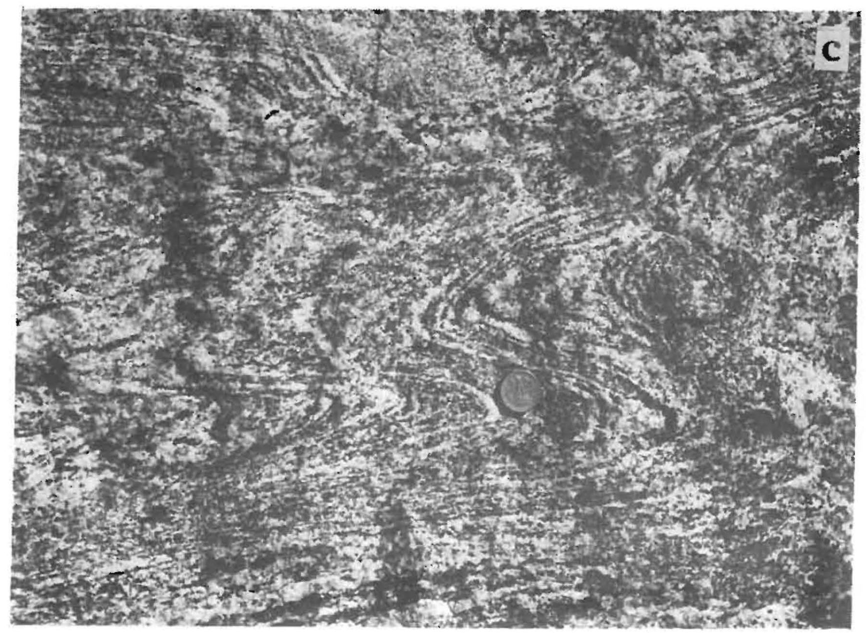
Plate II. High pressure Nilgiri charnockite



a. Ultramafic xenolith in 'massive' charnockite near Aravanakadu, Nilgiri Hills.



b. Phenomenon of retrogression in charnockite, Bhavanisagar quarry. Note the foliation 'coming out' prominently in the bleached-retrogressed areas. The foliation continues undisturbed from the dark charnockitic to bleached areas.



c. Earlier migmatitic structures in retrogressed and bleached charnockites. Fine shears can be noticed cross-cutting the migmatitic structures.

facies assemblages. During uplift and cooling, the strained grains of plagioclase, hypersthene and biotite did not recover, whereas the deformed and flattened quartz grains show partial to complete recystallization into a granoblastic mosaic texture which has developed along the margins. Minor hydration, e.g., formation of greenish hornblende and cummingtonite from the breakdown of hypersthene is common and becomes intense near the shear belts.

Major and trace element geochemistry of Nilgiri charnockites indicate that they are granitic to granodioritic in composition (Table VI). An igneous origin for the protoliths of charnockites is inferred from their major, trace and REE characters which resemble, calc-alkaline igneous suites (Condie and Allen, 1984; Srikantappa et.al., unpublished data). U-Pb dating of zircons from the Nilgiri Hills has given an age of 2535 m.y.(Buhl, 1987) (Fig.8).

Pyroxenite and gabbro

A significant lithological feature of the Nilgiri charnockite massif is the occurrence of numerous conformable lenses and pods of pyroxenite and gabbro. These bodies show sharp contacts with the charnockite. Ultramafic enclaves (Pl.II, Fig.a) often exhibit garnet-biotite rich contact metasomatic zones and are veined by quartzo-feldspathic mobilizates. Major and trace element composition of pyroxenite and gabbro are presented in Table VI. Chemistry of pyroxenites is comparable to picritic basalts.

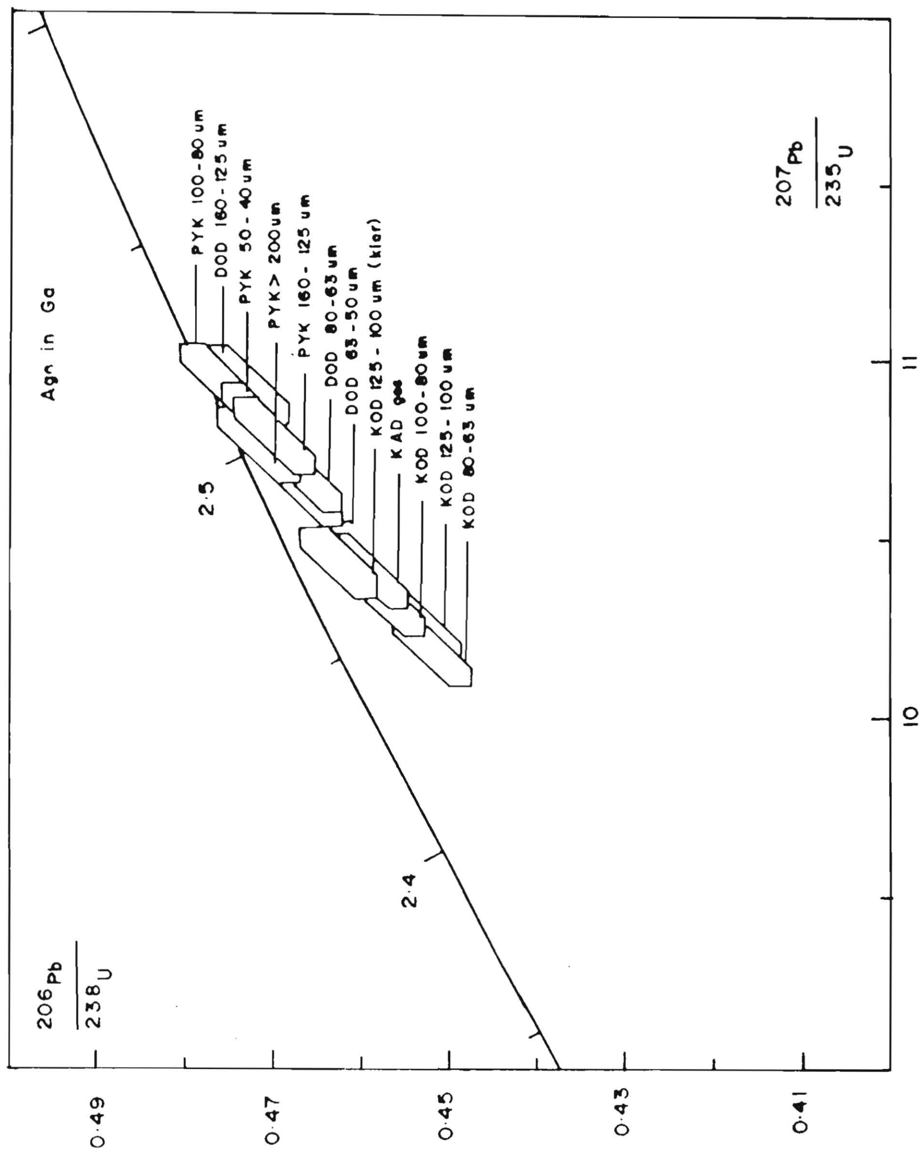


Fig. 12

Figure 8. Condordia diagram for U/Pb ages of charnockites from Nilgiri hills (after Buhl 1987).

TABLE: VI

CHEMICAL ANALYSES OF CHARNOCKITES FROM NILGIRI HILLS

	1	2	3	4	5	6	7	8	9
	478	480	567	569	76	107	11-1B	11-3D	GN-3B
SiO_2	72.61	67.96	59.39	70.24	66.73	77.72	69.90	69.00	67.10
TiO_2	0.37	0.54	0.68	0.49	0.43	0.16	0.44	0.29	0.34
Al_2O_3	11.85	14.72	16.84	12.03	14.24	12.51	13.50	14.60	15.20
Fe_2O_3	7.15	5.11	10.70	7.64	6.54	3.68	5.93	6.08	5.56
MnO	0.09	0.05	0.13	0.10	0.17	0.10	0.04	0.05	0.05
MgO	2.28	2.74	4.01	3.14	2.79	0.17	1.97	1.80	1.65
CaO	3.53	2.94	3.80	2.67	3.02	2.22	1.98	5.32	3.93
Na_2O	2.02	3.57	2.62	1.97	2.83	1.54	2.81	3.84	4.50
K_2O	0.49	2.30	1.02	0.97	1.50	0.90	3.91	0.64	1.06
P_2O_5	0.07	0.15	0.14	0.09	0.17	0.04	0.12	0.05	0.10
LOI	0.79	0.51	0.27	0.24	1.03	0.75	0.62	0.39	0.31
Total	101.25	100.59	99.61	99.57	99.45	99.79	100.99	100.26	99.80
Trace elements in PPM									
Cr	108	65	268	207	45	-	239	267	164
Ni	19	25	136	111	28	109	-	-	-
CO	17	16	36	21	105	135	-	-	-
Zr	95	82	68	127	73	285	140	110	50
Rb	7	71	24	18	13	13	60	10	10
Sr	167	363	227	227	258	234	320	180	420
Ba	12	8	25	15	786	148	1200	150	450

Sample No.1-4 (Condie, et.al. 1984)

Sample No.5-6 (Ashamanjari, unpublished data).

Sample No.7-8 (Janardhan et.al, 1982)

TABLE **VII**

CHEMICAL ANALYSES OF PYROXENITES & GABBROS FROM NILGIRI HILLS, MOYAR AND BHAVANI SHEAR ZONES

	N149/2	N170/3	N156/2	N169/1	N146/1	N172/2	N188	295II
SiO_2	49.70	46.43	46.80	52.67	51.90	44.34	45.85	48.78
TiO_2	0.42	0.53	0.48	0.30	0.52	1.15	1.12	0.75
Al_2O_3	10.58	7.84	12.98	11.42	14.03	21.04	14.45	13.95
Fe_2O_3	7.94	13.36	8.95	13.18	9.80	6.86	14.80	12.72
MnO	0.16	0.41	0.06	0.23	0.34	0.16	0.41	0.25
MgO	23.40	16.71	16.29	7.98	7.93	5.46	6.13	7.77
CaO	6.73	8.14	8.54	11.91	12.36	14.72	12.80	11.00
Na_2O	0.38	1.16	0.84	1.96	2.33	3.15	2.04	2.14
K_2O	0.76	2.21	2.03	-	0.28	2.12	-	0.75
P_2O_5	0.19	0.09	0.30	0.09	0.10	0.03	0.13	0.03
LOI	0.40	2.20	2.20	nd	0.80	0.47	2.20	0.32
	100.66	99.08	99.47	99.74	100.39	99.50	99.93	98.46
Cr	700	481	1060	295	141	160	69	nd
Ni	823	278	92	106	43	30	15	nd
CO	338	61	42	99	29	28	41	nd
Zr	192	43	nd	49	52	nd	85	nd
Rb	nd	121	64	nd	nd	nd	2	nd
Sr	556	30	59	128	137	385	105	nd
Ba	587	350	80	150	107	nd	49	nd

Data from Srikantappa et al., (1986)

The gabbroic rocks in the Nilgiri charnockite massif, in contrast to the ultramafic enclaves, occur as larger bodies, from a metre to few hundreds of metres wide and extending for several kilometres and conformable to the regional foliation (Srikantappa et al, 1986). There is considerable compositional variation from gabbro to anorthositic gabbro within single bodies which is attributed to magmatic differentiation. The gabbroic rocks in general show only minor penetrative deformation and their coarse-grained gabbroic texture, despite the thorough metamorphic recrystallization at granulite grade, is still preserved. Small bodies, however, are more intensely deformed and the original gabbroic texture has been stretched and flattened.

Garnetiferous two-pyroxene granulite (ferrogabbro) occurs as extended bodies, conformable to the regional foliation within the main massif, and in the Moyar and Bhavani shear belts (Fig.7). A set of mafic clinopyroxene-plagioclase rocks occur as dykes and show typical ophitic texture.

Auto retrogression has affected all the rock types within the Nilgiri granulite terrane in addition to the intensity of post-granulite facies shear-induced deformation. Orthopyroxene and clinopyroxene show exsolution lamellae of pyroxene phases and opaque minerals. Exsolution of opaque minerals is also common in hornblende and garnet. Coarsening and migration of the exsolved Fe-Ti oxide phases to the fractures and grain boundaries, occurred during advanced stages of retrogression. Formation of secondary calcic hornblende, cummongtonite and biotite along grain boundaries of pyroxene indicates minor rehydration during uplift and cooling of the rock complex.

Conditions of Metamorphism

The P-T conditions of metamorphism for the Nilgiri granulite terrane have been estimated from the compositions of co-existing minerals in charnockite, pyroxenite and gabbro (Janardhan et al, 1982; Raith et al, 1983; Raase et al, 1986; Srikantappa et al, 1986). Table VIII gives the representative chemical analyses of various mineral assemblage of the Nilgiri Hills.

Orthopyroxene: Orthopyroxene of the charnockitic rock types is mostly hypersthene with composition falling in the field of bronzite and ferrohypersthene (X_{Mg}=0.44-0.73). Al_2O_3 content of orthopyroxene is high with an average of 2.2 wt % for the Nilgiri charnockites (Table VII) in contrast to the low averages of 1.2 wt % obtained for low-land Kabbal type charnockite (Janardhan et.al.1982).

Orthopyroxene ranges in composition from bronzite (X_{Mg}=0.68-0.75) in the pyroxenite to hypersthene (X_{Mg}= 0.58-0.66) in gabbro.

Clinopyroxene: Clinopyroxene in charnockites shows narrow range of X_{Mg} values varying from 0.60 to 0.80 (Table VII). Similar to orthopyroxene, clinopyroxene

TABLE VIII

MICROPROBE ANALYSES OF SELECTED MINERALS FROM CHARNOCKITE OF NILGIRI HILLS

	ORTHOPYROXENE							CLINOPYROXENE			
S.A.No.	11-1B	11-3D	GN-3B	61I	83I	294KI	295II	11-3D	83I	294I	295III
SiO_2	49.80	50.80	51.50	50.97	50.50	49.69	51.18	51.20	51.20	49.34	50.22
Al_2O_3	3.30	2.10	2.40	2.20	1.28	2.26	1.61	3.20	2.06	4.55	4.26
FeO	26.10	30.00	25.40	23.39	30.50	28.15	26.89	14.10	13.70	11.35	10.63
MnO	0.00	0.00	0.06	0.11	-	0.68	0.59	0.00	0.22	0.25	0.17
MgO	20.50	16.00	19.90	21.47	17.00	17.98	19.43	11.00	11.40	10.49	11.11
CaO	0.02	0.80	0.40	0.15	0.60	0.59	0.35	20.70	20.90	21.23	21.70
Na_2O	--	--	--	--	--	--	--	0.08	0.46	1.14	1.25
Total	99.90	99.70	100.70	97.29	99.88	99.35	100.02	101.00	99.94	98.15	99.34

	GARNETS						HORNBLENDE		BIOTITE
S.A.No.	11-1B	GN-4A	61I	83I	294I	295III	1133D	303III	11-1B
SiO_2	37.70	38.40	38.10	38.40	38.18	38.50	42.60	41.00	38.10
Al_2O_3	21.70	21.50	21.42	21.60	20.80	21.29	13.80	12.84	15.00
FeO	29.40	26.50	28.36	27.30	25.95	26.63	16.40	12.99	11.80
MnO	0.60	1.00	0.46	0.96	1.45	0.98	0.00	0.08	0.00
MgO	8.20	6.30	7.10	5.27	7.85	6.64	9.70	11.70	16.60
CaO	2.10	6.20	3.26	6.59	6.40	6.61	12.00	11.54	0.30
Na_2O	--	--	--	--	--	--	0.80	2.65	0.00
K_2O	--	--	--	--	--	--	1.90	0.74	10.00
TiO_2	--	--	--	--	--	--	1.70	2.56	4.80
Total	99.70	99.90	98.70	100.12	100.63	100.69	98.90	96.10	96.10

Sl.No.	Sample Location
1.	11-1B Charnockite, Doddabetta
2.	11-3D Charnockite, Pykara.
3.	GN-3B Charnockite, Northern slopes of Nilgiri hills.
4.	61I - Gar-opx-K-feldspar-plag-gneiss; Doddabetta.
5.	83I - Mafic gar-pyx-plag-rock; 5 km East of Coonoor.
6.	294I - Gar-Pyx-plag rock; 13 km NE of Gudalur.
7.	295III - Mafic Gar-Hbl-pyx-plag rock; Masinigudi.
8.	303III - Mafic Hbl-plag-Gar-pyx rock; 3 km NW of Naduvattam
9.	GN-4A - Charnockite, Northern slope.

Sample Nos. 1-3 and 9 are from Janardhan et.al, 1982.

Sample Nos. 4-8 are from Raith et.al, 1983.

in high-pressure Nilgiri granulites show higher concentration of Al_2O_3 varying from 2.00 to 4.55 wt %. These features are related to higher temperature and/or pressure of crystallization of Nilgiri charnockites. Compositional zoning of some of the clinopyroxenes reported (Fig.6 in Raith et. al., 1983) reflects incomplete re-equilibration during falling temperatures. Compositional zoning is observed with increase in Ca and Mg towards the margin of the grain with decrease in Fe and Al and to a lesser extent Na and Ti. Thus, during retrograde metamorphism clinopyroxene solid solution changed by diffusion process towards diopside-rich compositions. Clinopyroxene from the pyroxenite is higher in Mg (X_{Mg}=0.8 to 0.9) and lower in Al (0.11-0.16 atoms p.f.u), when compared to those of the gabbroic rocks (X_{Mg}=0.63 to 0.80; Al = 0.15-0.25 atoms p.f.u.).

Plagioclase: Plagioclase shows varying anorthite content from An_{27} to An_{50}, and its composition is dependent on mineral assemblage which reflects the influence of bulk rock chemistry.

Plagioclase in pyroxenite and gabbro is andesine to labradorite and occasionally exhibits compositional zoning with An content decreasing towards the margin of the grains. Scapolite occurs in several gabbroic rocks as a stable phase with plagioclase. Its composition is meionitic (75 mole % Me), thus indicating a CO_2-rich fluid regime (Srikantappa, et.al, 1986).

Garnet: Garnet of the charnockite is essentially solid solution of the end members almandine, pyrope and grossular. Though garnet appears unzoned, distinct compositional zoning with different trends in different assemblages has been reported (Raith et. al, 1983).

Garnet is rare in pyroxenitic rock types and is characterised by a limited compositional variation 35-31 pyrope; 47-52 almandine, 17-18 grossular. In the gabbroic rocks garnet composition is more variable and generally higher in the almandine component (21-31 pyrope, 50-59 almandine, 15-22 grossular). In some of the mafic granulites a new generation of grossular-rich garnet ($>$ 23 mol %) has formed as symplectitic intergrowths with quartz by breakdown reaction involving pyroxene, plagioclase and opaque minerals.

Amphiboles: Amphibole from pyroxenite and gabbro is hastingsitic to pargasitic hornblende (Table VIII) and falls in the compositional fields of amphibole of mafic granulites from southern India (Raase et. al, 1986). The hastingsitic to pargasitic hornblende contain highest values of 0.18 to 0.29 Ti (atoms p.f.u.). Higher Ti content of these amphiboles is related to their high temperature of formation, as the entry of Ti into the structure of amphibole in natural assemblage is mainly temperature dependent (Raase, 1974).

Biotite: Biotite in the Nilgiri Hills shows varying X_{Mg} values ranging from 0.57 to 0.71. TiO_2 content varies from 4.9 to 5.4 wt % (Janardhan, et. al., 1982).

P-T estimates

Metamorphic conditions in the Nilgiri charnockite massif have been evaluated using several geothermometers and geobarometers applicable to clinopyroxene - orthopyroxene and garnet-pyroxene-plagioclase-quartz assemblages. Janardhan et. al, (1982) have reported temperature range of 750-880°C and pressures of 6.70 to 7.4 for the Doddabetta and a higher pressures of 9.1 Kb for northern slopes around Gudalur. Raith et. al, (1983) report a mean temperature of 720$\pm$83°C and pressures of 6.6$\pm$0.6 Kb, which match fairly well with the estimates of 735°C and 6.4 Kb reported by Harris et. al, (1982). Raith et. al, (1983) derived a higher pressure of 9.3$\pm$0.8 Kb for northern foot of the Nilgiri Hills when compared to those for the Nilgiri upland massif. This difference in pressure is attributed to southward tilting of the Nilgiri block (Harris, et. al, 1982; Raith et. al, 1983). Srikantappa et. al, (1986) based on orthopyroxene-clinopyroxene in pyroxenite and garnet-orthopyroxene-clinopyroxene-plagioclase and quartz assemblage in gabbroic rocks derive a mean temperature estimate of 770°$\pm$60°C and 8.0 to 9.5 Kb. The higher pressures of 9.5 Kb obtained in the central part of the Nilgiri Hills mainly for the maffic gabbro (ferro-gabbro) suggest the effect of bulk composition in pressure estimates. The higher pressure estimates of about 7-9.5 Kb obtained for the Nilgiri charnockite massif in southern India indicate that the terrane was burried to a depth of about 35 km during granulite facies metamorphism about 2.6 Ga ago. Assuming that no significant addition to the lower crust has occurred since that time, a considerable thickness of about 65-75 km for the late Archaean/early Proterozoic crust could be inferred from the present-day depth of the Moho discontinuity (30-40 Km according to Kaila, et. al, 1979).

Fluid inclusions

Fluid inclusion studies in charnockites of Nilgiri hills reveal the occurrence of carbonic inclusions in quartz and garnet (Srikantappa, et. al, 1987). Their shape and size varies from irregular to oval to negative crystals. Fluid inclusions in garnet are accicular, measuring 10-35 μm in size. Melting point temperatures of CO_2 inclusions in the older strained quartz grains range from -56.6 to -58.0°C. Reconnaissance Laser Raman Spectroscopic results show that lowering of (T_m) CO_2 is caused due to presence of nitrogen (3-5 mol % N_2, Srikantappa, et. al, 1987). CH_4 contents are insignificant. Homogenisation temperatures (T_h) range from -50.3 to 29°C with two marked peaks at -30°C and 10°C. From these data CO_2 densities of 1.076 and 0.860 g/cm^3 are inferred. The high density data of fluid inclusions agree with the P-T conditions obtained from mineral geothermobarometry indicating their entrapment near peak metamorphic conditions.

Presence of late watery inclusions with low salinity (10-12 mole % equiv. NaCl) suggest increased water activity during retrogression of the charnockites in the Nilgiri Hills.

The source of CO_2 in the granulite facies rocks is debatable. Three models have been proposed: (1) CO_2 is derived from surrounding rocks during decarbonation reaction (Glassley, 1983) or oxidation of graphite during metamorphism (Kreulen and Schuling, 1982); (2) CO_2 represents residual fluid left after extraction of H_2O through dissolution in anatectic melts (Touret and Dietvorst, 1983) or (3) CO_2 is derived from the mantle (Newton et. al, 1980). In the absence of any anatectic melts in the Nilgiri granulite terrain and absence of carbonate rocks, the model of CO_2 derived from the mantle is considered as the most probable source (Srikantappa, 1987).

Moyar and Bhavani shear zones

Field investigations in Moyar and Bhavani shear zones indicate progressive retrogression of granulite facies charnockite as well as the associated pyroxenite and gabbroic rocks. As one approaches the shear zones, development of new shear fabric is noticed. Steeply dipping shear planes trending N 15°E, N 15°W and N 80°E mark the Moyar shear zone, N-S and N 70°E trending shears are common in the Bhavani shear zone. Along these shear planes, development of highly irregular, bleached and retrogressed areas are observed (Plate II, Figs. 'b' & 'c'). The greasy grey colour of the charnockite is selectively removed along the shear planes and as a result the original foliation of charnockite is laid bare. In contrast to the growth of pyroxene after hornblende or biotite along shear planes in pro-grade charnockitic areas as near Kabbal, here in retrogressed areas pyroxene is seen breaking down to anthophyllite/hornblende and biotite.

In the central part of the sheared zones, the development of a fissile biotite gneiss is common. The formation of K-feldspar dominant augen gneiss in these zones indicate intense potash metasomatism. This may be related to the emplacement of younger granites (cf. Punjai Puliampatti, Selvan, 1982). Another common feature seen in both Moyar and Bhavani shear belts, particularly along the margins of the Nilgiri charnockite massif is the occurrence of pseudotachylites. These features are related to the upliftment of the Nilgiri charnockite massif.

Taking into consideration the recent isotopic studies on granulites of the Nilgiris Hills (2.5 Ga, Buhl, 1987) together with the available field, petrological and geochemical data, the Nilgiri granulite terrane may be interpreted as a Cordillera-type plutonic belt generated through northward subduction, representing Proterozoic addition to the Archaean Dharwar craton to the north (Srikantappa et. al. 1986). The charnockites of the B.R.Hills give an older age of 3.4 b.y (U/Pb zircon ages, Buhl, 1987), when compared to the charnockites of Nilgiri Hills. Preliminary petrological and geochemical studies (Condie and Allen, 1984; Srikantappa, unpbl.data) indicate that the charnockites of B.R.Hills and Nilgiri Hills appear to be quite different. It appears most likely that the Moyar shear belt to the north of the Nilgiri Hills represents a major suture zone, which got reactivated several times during the early history of the earth.

Fluid inclusion studies in Moyar and Bhavani shear zones indicate that they have been modified considerably during retrogression. Presence of CO_2-rich, CO_2-H_2O and H_2O-rich inclusions have been recorded (Srikantappa, et. al., unp. data). In many of the sections studied, there is complete absence of fluid inclusions particularly in intensely sheared areas. This indicate degassing during shear deformation and fluid migration to higher levels. These features are taken as positive evidence for fluid transport and formation of low pressure charnockite (Stahle, et. al. 1987)

9. KERALA KHONDALITE BELT

Introduction

Kerala forms an important southern most segment of the Peninsular shield covered by rocks of Precambrian age. Outcrop pattern is dominated by a northern zone of massive charnockites and southern zone of a rock suite collectively known as Khondalite group (Fig.9). Tertiary and sub-recent formations flank the western portions of the belt. Most of the present field excursion is scheduled in the Kerala khondalite belt.

Granulite facies supracrustals of S. India Kerala, Khondalite belt.

The Kerala Khondalite Belt (KKB) is one of the largest terrains of granulite grade supracrustals in south India (150 x 80 km). The northern limit of the khondalite belt is marked by a NW-SE trending Achankovil shear, which is similar to other Proterozoic shear zones of south India (Drury et al 1984). A large portion of the Eastern Ghats are occupied by Khondalite group of rocks. This has prompted several workers to suggest that some portion of the Kerala belt may belong to the Eastern Ghat orogenic province (Narayanaswamy 1976). The Khondalite group consists of garnet-biotite ± graphite gneisses and intimately associated garnetiferous charnockite (+orthopyroxene), khondalites (graphite-sillimanite-garnet-biotite±cordierite), cordierite gneisses (garnet-biotite-

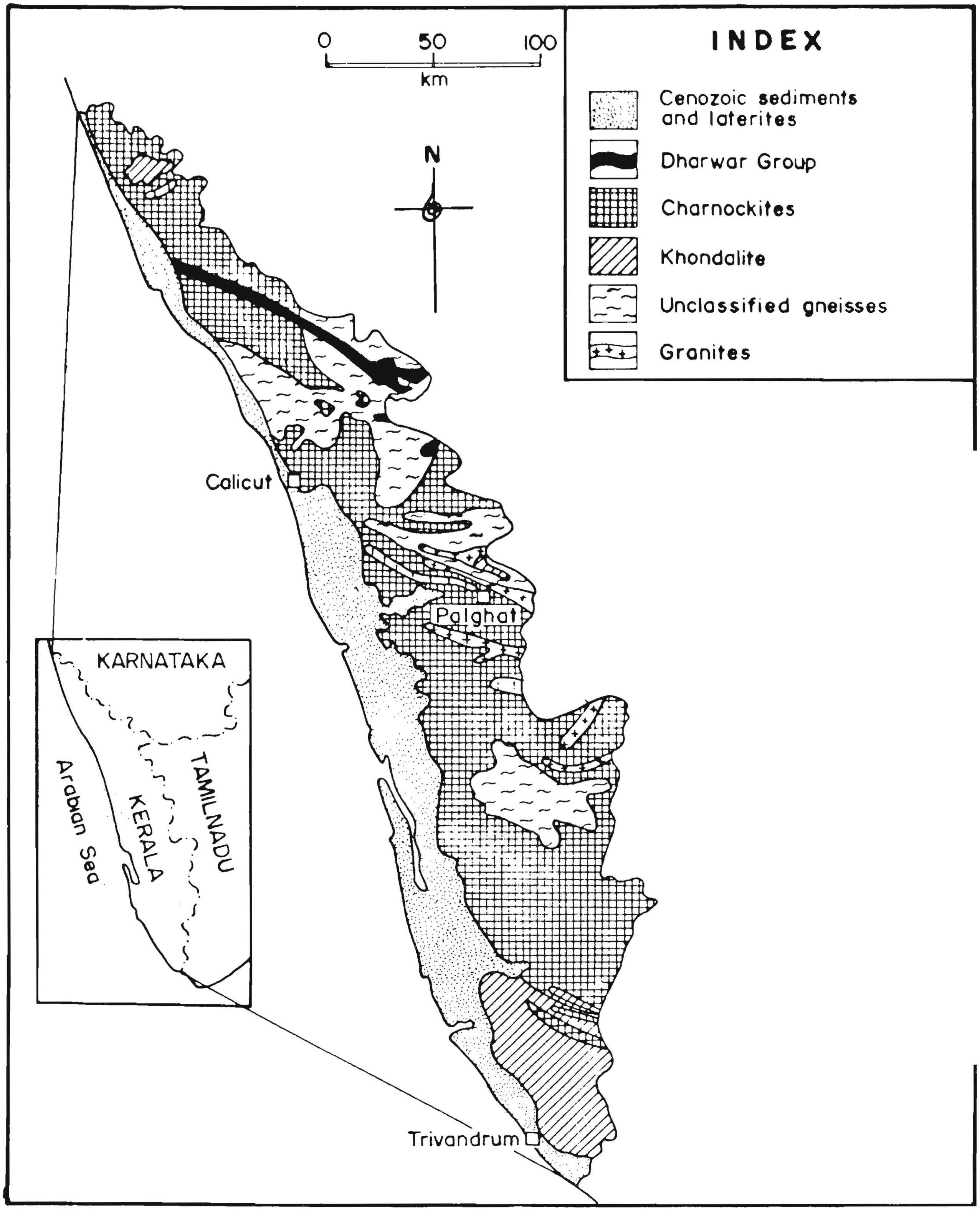


Figure 9. Geological map of Kerala.

cordierite$\pm$orthopyroxene) and less abundant calc-silicates, basic granulite and quartzites. Hence, most part of the khondalite belt represents deformed sequence of psammitic to pelitic sediments with calcareous intercalations, metamorphosed in upper amphibolite to granulite facies conditions.

The age and lithostratigraphic succession of the khondalite belt are not well understood. Crawford (1969) has reported four Rb-Sr whole rock ages ranging from 2155 - 3070 Ma. Some of the U-Pb ages produced by Odom (1982) cover the same range for charnockites and khondalites. These ages are similar to the ages of charnockite from other parts of southern India and therefore a late Archaean early Proterozoic metamorphism has affected the rocks of this region.

Earlier studies on the Kerala charnockites (Jacob 1962; Mahadevan, 1964; Narayanaswamy and Lakshmi 1967) suggested that charnockites are retrogressing to gneiss and, charnockite and khondalite intercalations have evolved from volcanosedimentary protoliths of geosynclinal origin. Recent studies have noted the arrested growth of charnockite involving isochemical transformation of gneiss to charnockite south of the opx isograd (12°45'N) (Ravindra Kumar et al, 1985; Srikantappa et al 1985; Ravindra Kumar and Chacko, 1986).

Maps: The present study areas are covered by Survey of India toposheets 58H/1, H/2, H/3, D/13, D/15, D/16.

Structure

The regional strike of foliation and secondary compositional bandings are dominantly NW-SE to WNW-ESE with a steep dip (55-85°) towards SW and SSW. Four deformations have been identified by Sinha-Roy (1983). His study suggests that the regional gneissocity and secondary compositional layering are related to the first deformation. These have been transposed to variable degree and occur now parallel to the axial planes of the folds of the second deformation. The second deformation structures are reclined to slightly inclined and have been refolded from their original orientation along NW-SE axis. The third deformation structures appear as large-scale upright folds on NNE-SSW axis. Faults and joints parallel to the coast are linked to the fourth deformation. Earlier regional studies (Narayanaswamy, 1976; Rao, 1978) had suggested blanket granulite facies metamorphism which was linked to the first deformation followed by an amphibolite facies event related to the second deformation. Greenschist facies metamorphism dominant in north Kerala is associated with the third deformation.

Yoshida and Santosh (1987) from their analysis of tectonics and microstructures in selected quarries around Trivandrum found four main events -

(a) flextural slip folding (F2) of the precursors of banded gneiss and charnockites, resulting in the development of close to isoclinal folds;

(b) development of open to close passive folds with axial plane schistocity/foliation (F3);

(c) formation of incipient charnockites with ductile deformation of the garnet-biotite gneiss and

(d) intrusion of biotite pegmatite and development of faint schistocity.

Nomenclature and mineralogy

The following is a brief description of dominant rock types observed in the Kerala khondalite belt. As there are large differences in naming and grouping of rocks, it is suggested for the present study that rocks be named with specific mineralogy. This description follows the original and most widely used names of the rock and will be adhered to in this field description.

Khondalite:

Khondalite is the name given by T.L.Walker (Mem.Geol. Sur.India, v.23, p.11, 1902) to para schists including garnetiferous quartz-sillimanite rocks with garnetiferous quartzites, calciphyres and graphitic schists interbanded with charnockite and granitic gneiss. The name is after Khond, a tribe inhabiting a part of Orissa.

Khondalite is the most widely seen rock type in the Kerala khondalite belt with a mineralogy of quartz+garnet+biotite+sillimanite+feldspar+graphite$\pm$cordierite$\pm$spinel$\pm$ rutile. In highly migmatised zones they form the restite portions. Approximate modal abundance of minerals in khondalite is garnet (10-25%), biotite 20-40%, sillimanite (5-25%,) feldspar (10-35%) and graphite (0.2-1%). Cordierite may be present with varying proportion of 2 to 15%. The garnet-biotite gneiss seen all over the terrain is the semipelitic equivalent of khondalite with significant absence of sillimanite.

Massif charnockite:

These are noted dominantly as masses to the north and south of khondalite group of rocks. Minor patches occur within the khondalite belt. The term massive charnockite is also used as a synonym to massif charnockite. Foliation is not conspicuous and garnet is normally absent. The mineralogy is orthopyroxene (5-10%), amphibole (2-15%), clinopyroxene (2-8%), plagioclase (10-40%) and quartz Biotite is scarce and usually is of secondary origin. Magnetite rather than ilmenite is the common opaque phase.

Basic granulite:

This is one of the important rock type normally present as dyke or sill-like intrusions in garnet-biotite gneisses. The rock is medium to fine-grained with characteristic granulitic texture. When seen in quartsofeldspathic gneiss, as at Malayankil and Kunnanpara it is mobilised and appears as broken and boudinaged folded enclaves. Coarse-grained recrystallisation similar to what is observed in incipient charnockitisation is commonly seen in the central part of these bodies showing evidences of quartzo-feldspathic penetration. This feature, however, post-dates the retrogression seen all along the margins between the mafic body and the quartzo-feldspathic material.

The rock is made up of clinopyroxene, orthopyroxene, plagioclase, hornblende, with or without garnet, biotite and quartz.

Incipient charnockites:

Incipient charnockites are generally coarser compared to the host rocks and occur as patches, veins or anastomising structures with greasy green colour in garnet-biotite gneisses. In addition to the mineralogy of the surrounding gneisses (garnet+biotite+K-feldspar+plagioclase (An 30-40)+quartz±graphite), orthopyroxene (2-10%) is present. The texture is homogenous granoblastic with no preferred orientation. Arrested growth is identified normally by the following criteria;

(1) Cross-cutting relation to the gneissic foliation. Emanating from these patches are tongues of charnockite spread out parallel to foliation.

(2) Coarse-grained recrystallized nature of charnockites which generally obliterate the gneissic foliation; only rarely relict foliation is preserved.

(3) Warping and doming of adjacent gneissic foliation with the development of charnockite.

(4) Common presence associated with shears or any weak linear structures. Charnockite formation is closely related to these shears.

Leptynite:

This term is used to refer to garnetiferous quartzo-feldspathic gneisses which are intimately associated with charnockites and khondalites. They normally consist of quartz, alkali-feldspar and sodic plagioclase near ternary minimum proportions. The rock is spotted with garnets, and biotite may be present (not always) up to about 10%. In quarries, leptynites may be found either as nebulous (foliation blurring) patches interrupting gneisses, or elongate concordant lenses. In highly migmatised khondalites, leptynites define tight isoclinal folds. Recently Srikantappa et al (1985) have used the term leptynitic gneiss to designate both grey garnet-biotite gneisses associated with incipient charnockites and the quartzo feldspathic acid gneisses/layers (leptynites). Presence of more than one generation of leptynites cannot be ruled out.

Cordierite-bearing gneiss:

Cordierite is an important mineral constituent of most of the supracrustal rocks of the KKB. However, at the northern margin of the KKB, a discontinuous wide zone dominated by cordierite in spatial association with Achankovil shear zone (eight to ten kilometres) is seen (Sinha-Roy et al, 1984; Santosh 1987). This has prompted many early workers to suggest shear controlled development of cordierite in this zone. The rock is generally coarse-grained with an essential mineralogy of cordierite, garnet, plagioclase, biotite and quartz.

Either sillimanite or hypersthene are normally present in the rock. Several mineral assemblages involving cordierite have been identified by Sinha-Roy et al (1984) and Santosh (1987). Santosh even reports the rare assemblage cord-hyp-sill-bio-qtz-Spi$\pm$plag. From the study of mineral association and reaction texture Chacko et al (1987a) and Santosh (1987) have suggested that cordierite producing reaction was driven by isothermal decrease of pressure during uplift.

Geochemistry

In Table-10, chemistry of the immediately adjacent gneiss-charnockite pairs, and of khondalite and mafic granulite from few localities described in the following sections, are presented. Major and trace element composition of gneisses and charnockites have comparable and identical chemistry, suggesting nearly isochemical metamorphism. There is a strong resemblance of major element chemistry of gneiss and charnockite to arkosic sediments while khondalites compare well with argillaceous sediments. The chemical similarity of garnet-biotite gneisses with granitic rocks-typical LREE enrichment with significant negative Europium anomaly suggest that clastic sediments were derived from a source region predominantly composed of K-feldspar-rich granitoid plutonic or gneissic rocks (Srikantappa et al 1985; Chacko et al, 1987). The low Ni contents and low MgO/FeO and Ni/V ratios also suggest a sialic provenance.

TABLE 10

Chemical compositions of selected gneiss (GN), Charnockite (CH), Khondalite (KH), Calc-silicate(CS), Massif Charnockite (MCH) and Mafic Granulite (MG) from south Kerala. Data from Ravindrakumar and Chacko (1985)[1], Srikantappa et al (1985)[2] and Chacko (1987)[3].

	PONMUDI[1]		KADAMAKOD[1]		KADAKAMAN[1]		MANNANTHALA[2]		KOTTA VATTAM	KALLAR[3]	PARI-PALLI[3]	
	GN	CH	GN	CH	CH	CS	GN	CH	CH	KH	MCH	MG
SiO_2	68.80	67.80	69.60	69.50	56.00	71.70	72.11	70.39	67.94	60.60	64.40	47.50
TiO_2	0.83	0.92	0.41	0.41	0.91	0.57	0.25	0.25	0.87	0.76	0.93	1.24
Al_2O_3	14.60	14.50	15.90	16.10	19.10	11.60	15.35	15.08	14.06	20.20	16.90	15.40
FeO^t	5.99	6.17	2.88	2.30	9.00	4.07	2.12	1.85	4.74	8.00	4.19	16.00
MnO	0.08	0.09	0.03	0.02	0.22	0.19	0.03	0.03	0.04	0.09	0.07	0.21
MgO	1.05	1.01	0.74	0.54	5.12	2.25	0.66	0.48	0.88	2.28	1.06	7.09
CaO	2.13	2.37	2.38	2.78	2.73	8.63	2.39	2.29	2.32	0.81	2.75	9.40
Na_2O	2.55	2.74	4.26	4.75	2.91	0.86	4.40	4.30	2.73	1.76	3.48	2.45
K_2O	4.42	4.54	3.03	2.12	2.50	1.24	1.23	2.26	5.29	4.19	6.05	1.07
P_2O_5	0.18	0.19	0.09	0.06	0.10	0.15	0.11	0.19	0.36	0.06	0.21	0.25
Total	100.63	100.33	100.06	98.58	98.59	100.66	98.59	97.19	99.23	98.75	100.04	100.61
Ba	830	920	640	420	1000	540	460	393	1093	1290	2860	210
Rb	233	202	123	77	75	47	8	70	207	191	165	6
Sr	156	179	275	240	249	255	274	299	112	234	501	124
Y	68	62	33	20	66	38	-	-	-	48	43	44
Zr	273	329	211	257	216	168	160	153	338	192	476	117
Vr	48	31	26	27	210	65	7	9	-	150	39	286
Cr	166	121	95	90	176	194	-	-	-	161	101	-
Ni	17	17	14	9	79	46	-	-	-	73	10	112

Geothermometry and geobarometry

The temperature-pressure data of the KKB are presented in Fig10. The paleotemperature range of 650-850°C is in conformity with phase equilibrium considerations. The paleopressure data is fairly uniform over the vast terrain within a narrow range of 4.5 to 6.5 Kbar (Fig.10). The progressive mineral reactions noted in the supracrustals are consistent with the continuous P-T cycle. Chacko et al (1987) inferred a mechanism, similar to 'A subduction' hypothesis, applied by Hodges et al (1982) to the Norwegian Caledonides, as responsible for the nearly uniform burial of khondalite belt precursor sediments at depths of 15-20 km.

Fluid inclusion studies

Significant progress has been made to characterise the nature of fluids in the granulites of south Kerala (Santosh, 1986, 1987). These studies suggest that CO_2 is the dominant ambient fluid species in granulites. Chronologically early carbonic fluids occur entrapped within inclusions (Figs.11 & 12) in charnockites and khondalites. These CO_2-rich fluids with high density in charnockite (0.95 gm/cm^3, Santosh, 1986), and khondalites (0.93-0.97 gm/cm^3, Santosh, 1986), probably characterise fluids present at or close to the peak stage of deep crustal metamorphism. Since their isochores pass through the P-T region delineated from mineral chemistry, they define a pressure range of 4.6 - 6.1 Kbar. Incipient charnockites have greater number of arrays of optically dense, CO_2-rich fluid

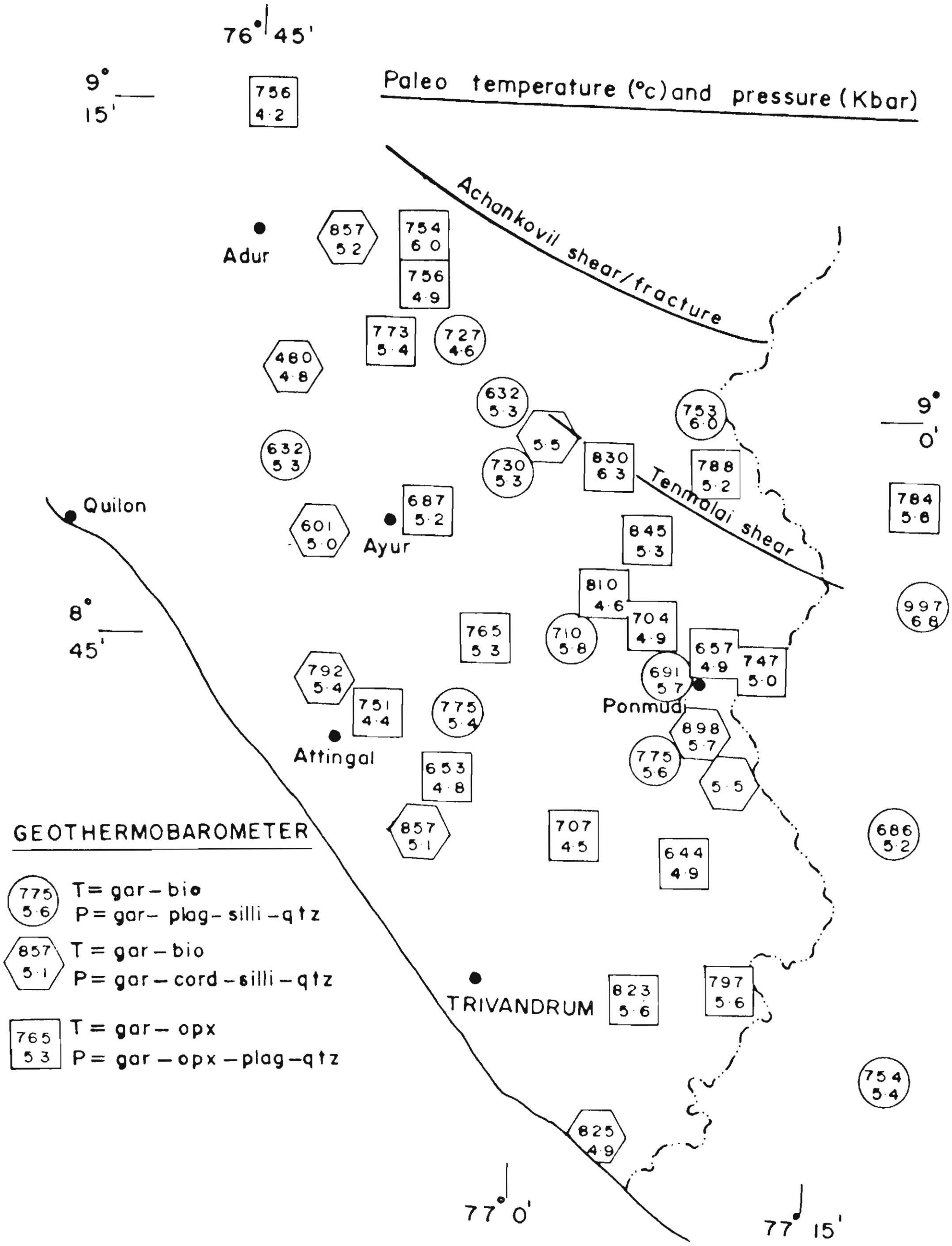


Figure 10. Palaeo-pressure and palaeo-temperature distribution in Kerala khondalite belt (details see Chacko et al, 1987).

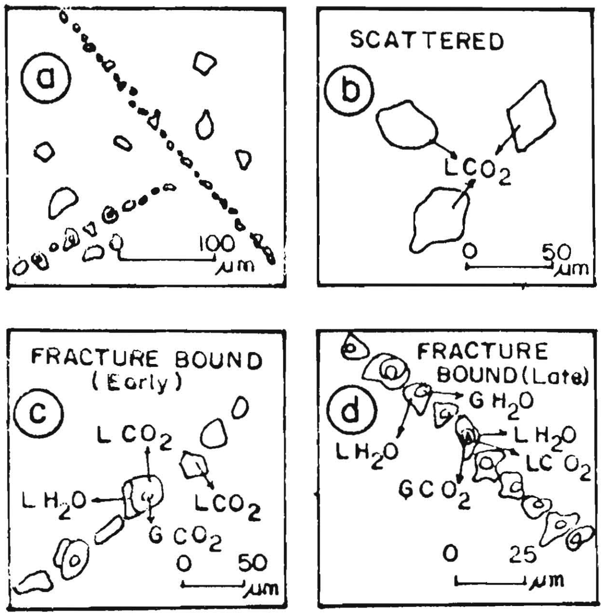


Fig.11 (a, b, c, d)
Distribution of different phase composition of fluid inclusions in charnockite (after Santosh, 1986).

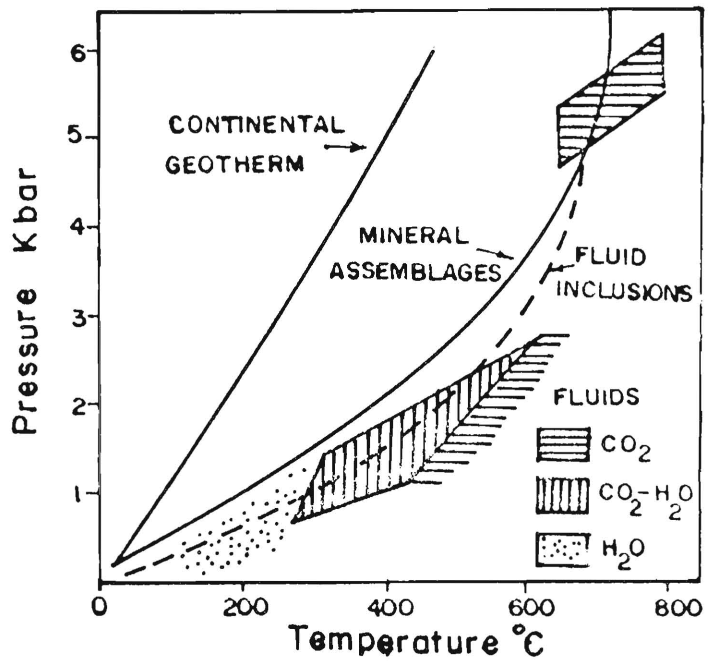


Fig.12 Diagram after Santosh
Diagram after Santosh (1985) depicting piezometric array of south Indian charnockites as defined from their fluid evolution.

inclusions (0.90 gm/cm^3) in quartz, essentially occupying healed fractures (Ravindra Kumar et al, 1985; Hansen et al, 1987). The implied density in incipient charnockite, yielding pressure of 3-4 Kbar, however, indicates their entrapment at lower pressure than the mineralogically inferred pressure (5-6 Kbar).

Pseudo secondary type of CO_2 and CO_2-H_2O inclusions coexist in rehealed fractures. Monophase inclusions of this category define densities of 0.65 - 0.75 gm/cm^3) in charnockites and 0.73 - 0.75 g/cm^3 in khondalites (Santosh, 1986, a,b). The CO_2 phase in the CO_2-H_2O inclusions have a peak density of 0.70 gm/cm^3. Aqueous biphase inclusions in both the rock types are generally water-rich with very low NaCl concentration with densities of 0.80 - 0.89 g/cm^3 in charnockites and 0.57-0.79 gm/cm^3 in khondalites. Calculations based on P-V-T properties yield estimates of 2.2 Kbar and 510°C for the entrapment of coexisting CO_2 and CO_2-H_2O inclusions in charnockites. In khondalites the MRK derived isochores for mixed carbonic aqueous inclusions intersect the low density CO_2 isochores at 250°C and 0.8 Kbar.

A near isothermal uplift history has been inferred based on combined fluid and solid data.(~~Fig. 2~~). More details on the fluid inclusions characteristics of gneiss-charnockites and khondalites can be found in Santosh (1985, 1986a,b, 1987); Hansen et al (1987) and Srikantappa and Ravindra Kumar (1987).

Geochronology

Geochronological data on Kerala khondalite are scarce. Early isotopic work by Crawford (1969) gave whole-rock, model Rb-Sr ages of 2155 and 3070 m.y. for a charnockite and khondalite of Trivandrum district respectively. U-Pb zircon dating of garnet-biotite gneiss and charnockites by Odom (1982) has yielded ages of 2838±40 and 2930±50 m.y. Recent zircon studies on Ponmudi (see itinerary 2, stop 5) charnockites gave lower intercept of discordia through 540 m.y. and the upper intercept at 1930 m.y. indicating a late-Proterozoic age of metamorphism (Srikantappa et al, 1985). Srikantappa et al (1985) interpret 540 m.y. as the principal age of granulite facies metamorphism. More recently khondalite samples have given poorly defined Rb-Sr isochron, indicating an approximate age of 2100 Ma (Chacko, 1987), while cordierite gneisses and charnockites from Achankovil yield a good Rb-Sr ages of 670 ± 8 m.y. and 660 ± 45 m.y. respectively (Iyer and Santosh, 1987). Hence, thermal overprint of Pan African ages of 500-600 m.y. in southern India (Hansen et al, 1985; Santosh et al 1987a) and Sri Lanka and a possibility of polymetamorphism of supracrustal assemblages of the KKB, is indicated. Available geochronological data on the rocks of the Kerala khondalite belt and adjoining areas are presented in Table- 11.

Table 11. Age data of the KKB supracrustals and associated rocks.

Rock/Mineral	Age (M.Y)	Method	Locality	Reference
Gneiss/Zircon	700 ± 200	U-Pb	Capecomorin	Vinogradove and Tugarinov (1964)
Gneiss	2180	Rb-Sr	Ayoor	Crawford (1969)
Gneiss	3070	Rb-Sr	Pandaplavu	Crawford (1969)
Cordierite gneiss	670 ± 8	Rb-Sr	Chenganoor	Iyer and Santosh (1987)
Gneiss/Zircon	2838 ± 40	U-Pb	Nedumannur	Odom (1982)
Charnockite	2155	Rb-Sr	Ayoor	Crawford (1969)
Charnockite	2780	Rb-Sr	Kizhaikonam	Crawford (1969)
Charnockite/Zircon	2930 ± 50	U-Pb	Nedumannur	Odom (1982)
Charnockite/Zircon	540	U-Pb	Ponmudi	Srikantappa etal (1985)
Charnockite	660 ± 45	Rb-Sr	Chenganoor	Iyer and Santosh (1987)
Khondalite	2100	Rb-Sr	Kallar	Chacko (1987)

Development of the KKB and granulite facies metamorphism

The field, petrographic and geochemical studies suggest that the metasedimentaries are dominantly made up of metamorphosed equivalents of pelitic (khondalite) to semipelitic (gar-bio gneisses) argillaceous rocks, sandstones (quartzites) and marbles (calc-granulites). Incipient charnockites compare chemically with clastic sediments and granitic igneous rocks (Srikantappa et al, 1985, Chacko et al, 1987). This points to surficial origin and an upper crustal history prior to granulite facies metamorphism, and presence of a large amount of initial H_2O in these rocks. Existence of such large tracts of supracrustal rocks in south India and arrested charnockite formation in them raises several important questions about the source of sediments, nature and development of the depositional basin and mechanism of burial of sediments to great depths of 15-25 km for granulite facies metamorphism (Chacko et al, 1987).

The association of arkose-pelite lithologies and lower mafic compositions of the rocks have been cited as evidence for derivation of sediments from a sialic source and deposition in a cratonic rift basin. Based on field and textural evidences Chacko et al (1987) have identified the following sequence of events ensuing deposition in the KKB:

(a) migmatisation and development of compositional layering in khondalites and gneisses;

(b) charnockitisation disrupting the foliation;

(c) development of second generation cordierite and symplectites of gar-cord in khondalites with uplift.

The possible metamorphic path of the KKB rocks is shown in Fig.13 as depicted in Fig.5 of Chacko et al (1987).

The model calculation of Hansen et al (1984) suggest that the minimum requirement for opx formation (second event) is that the activity of H_2O be < 0.3 at 6-8 Kbar pressure and 750°C temperature (the solid phase P-T range of KKB: Chacko et al 1987). Hence, the development of incipient charnockites in the paragneisses of KKB requires a mechanism of expelling all this water out of the system. Any model explaining the evolution of the KKB and the mechanism which lowered P_{H2O} for charnockite development should also account in its history, the spatio temporal relation between massif and incipient charnockite and the related granulite facies metamorphism.

Taking note of the presence in large quantities of CO_2-rich fluids in incipient charnockites of the KKB, carbonic metamorphism aided by streaming of CO_2-rich fluids from deeper source was considered applicable to the development of incipient charnockites in KKB (Ravindra Kumar et al, 1985; Ravindra Kumar and Chacko 1986; Santosh 1985, 1986). Srikantappa et al (1985) taking evidences from mineralogical criteria and presence of same density fluid inclusions in adjacent gneiss and charnockite has advocated an alternative hypothesis of isothermal decrease of fluid pressure leading to the development of charnockites.

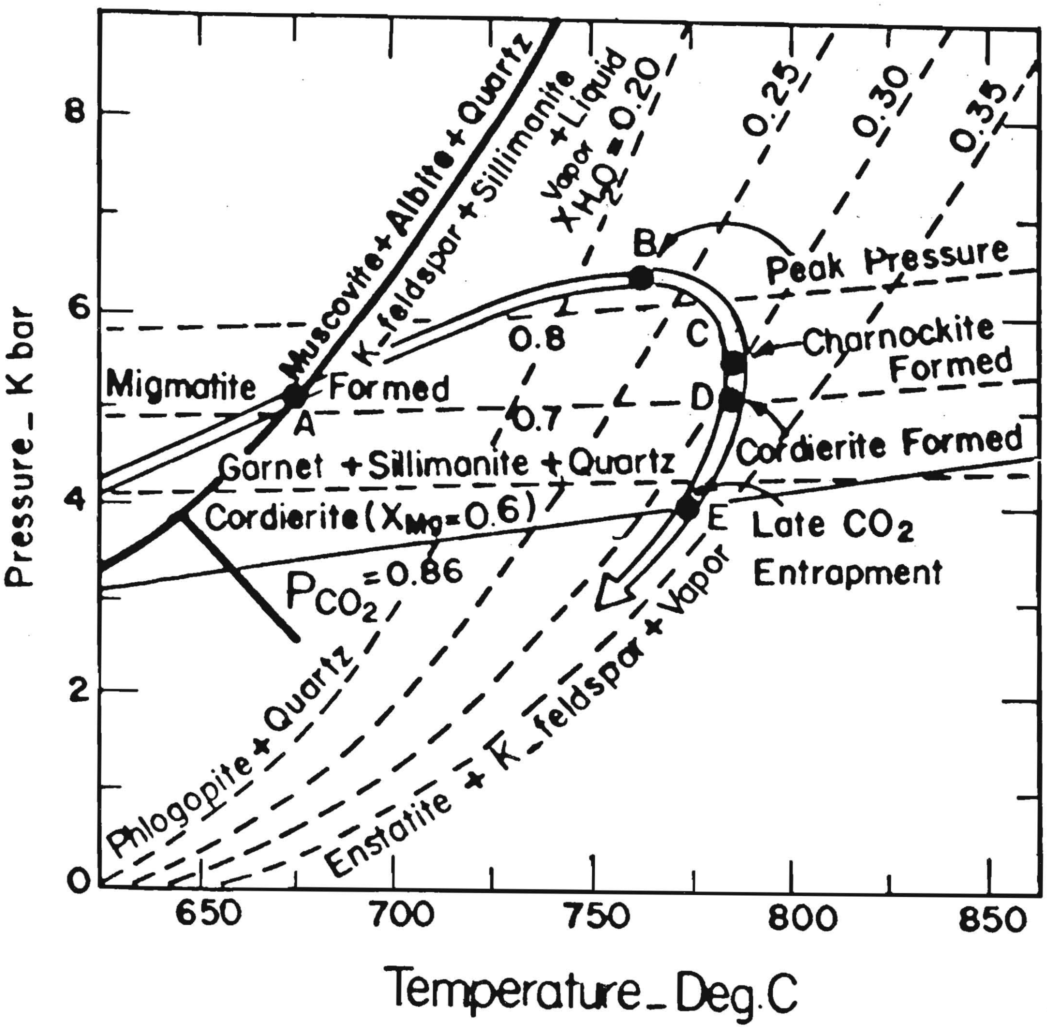


Fig.13. A P-T trajectory of possible metamorphic path of the KKB rocks (after Chacko et al, 1987).

Hansen et al (1987) have recently doubted the applicability of CO_2 influx model to the Ponmudi type charnockite formation, favouring the possibility of orthopyroxene and CO_2-rich fluids developing internally by biotite reaction with graphite, without intervention of externally derived fluids. Recent stable isotope data of fluid inclusion (Santosh, 1987b) point that there was at least a minor amount of flushing of CO_2. Perhaps more detailed work on similar lines and on oxygen isotopes of the KKB rocks would help in deciding on external/internal or combined sources of CO_2 fluids in the development of the KKB.

PART II

FIELD GUIDE

THE KOLAR SCHIST BELT - A POSSIBLE ARCHAEAN SUTURE ZONE

Day—2

January 10, 1988

Guides

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Programme

Time		
0830		Leave Bangalore for Kolar (80 km)
1100	Stop 1	Mysore Granite Works - 2 km west of the western margin of the belt.
1200	Stop 2	Mudgy's Corner - western margin of the schist belt.
		Lunch break
1400	Stop 3	East side - 2 km east of the schist belt margin.
1600	Stop 4	Eastern margin, west of the village Peddapalli
1700		Leave for Bangalore
1900		Reach Bangalore

The Kolar Schist Belt is about 80 km east of Bangalore. Multiply deformed, migmatitic granitoid rocks, known as the Peninsular Gneiss, are the major rock type between Bangalore and the Belt. Because of intense lateritic weathering exposures of this gneiss are scanty. Near the town of Kolar, less deformed granitoid rocks occur in the form of large hills and these could be later intrusives into the Peninsular Gneiss. Four stops are planned to show the major aspects of geology of the area near Kolar Gold Fields (KGF). Stop 1 is on the west side of the belt to see the two major gneissic units on the west, the Dod and Dosa gneisses. Stop 2 is on the KGF to Kamasamudram road to see the amphibolite, iron formation, shear zone marginal to the schist belt and the Banded Gneiss, on the western margin of the belt. Stop 3 is on the east side to see the Kambha Gneiss. Stop 4 is to see the Champion Gneiss near the village of Peddapalli. The stops and the route are shown in Fig.1.

Stop 1 Mysore Granite Works - 2 km west of the western margin of the belt

2632 Ma Dod and 2613 Ma Dosa gneisses are exposed here. The Dod Gneiss (sample No.69) is the melanocratic variety, characterized by equigranular texture, the presence of both hornblende and biotite and sphene and relatively smaller amounts of quartz. The Dosa Gneiss (Sample No.25) is relatively leucocratic, commonly coarser grained and inequigranular with megacrysts of alkali feldspar. It has

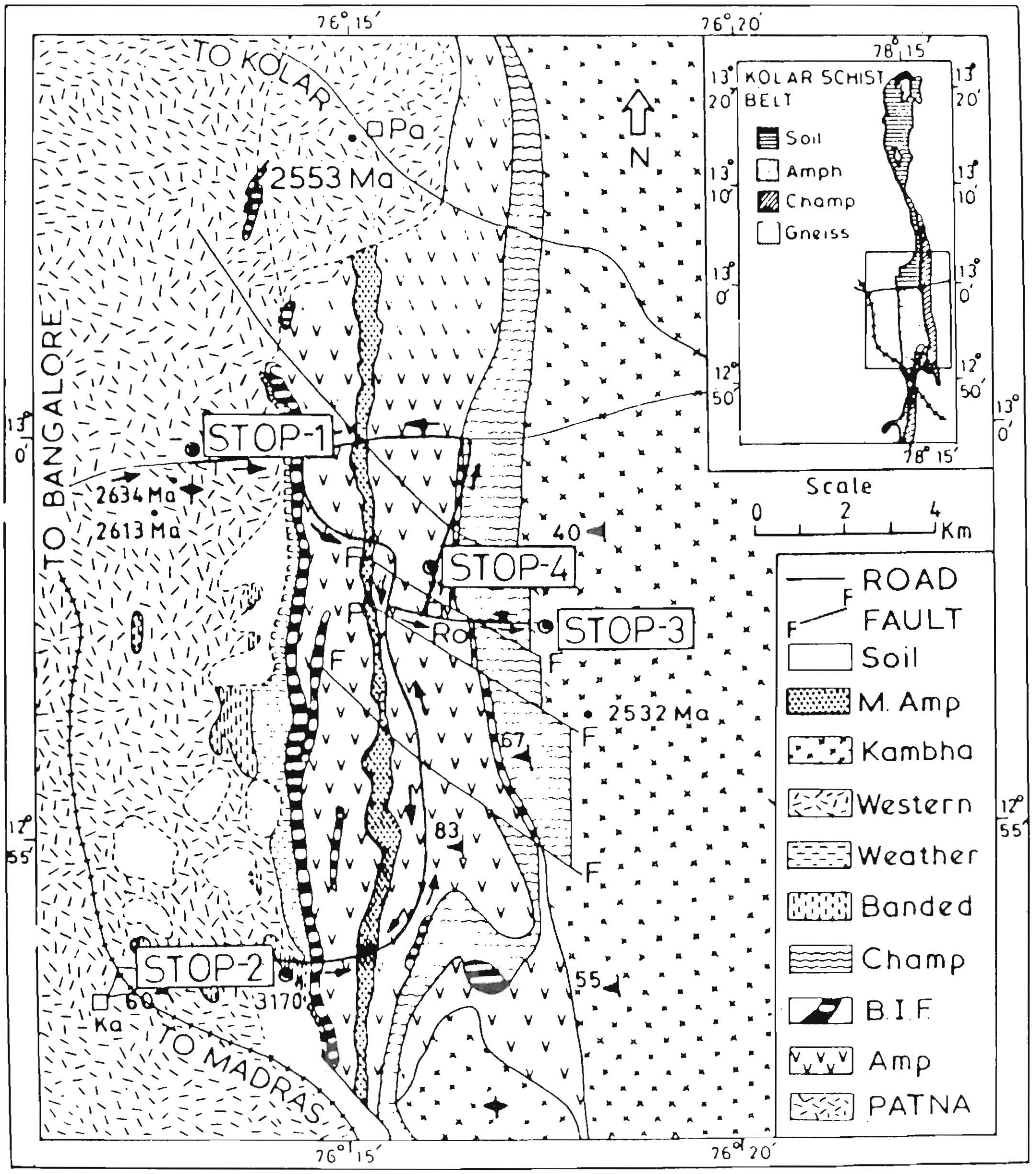


Figure 1 Geological map of the central Kolar Schist Belt. The heavy line indicates the route to be followed for the field conference with locations of four stops. Ages of major granitic gneisses are also indicated. Ka, Ro and Pa refer to Kamasamudram, Robertsonpet and Patna.

higher proportions of quartz. Biotite is the dominant mafic phase. Accessory amounts of sulfides are common. Towards the east, closer to the belt, the Dod Gneiss is dominant. Further west, the Dosa Gneiss is dominant. There exists a gradation in mineralogy between the two types of gneisses. In the vicinity of the Stop 1, each type enclosing the other is commonly seen.

The gneisses are commonly foliated. The foliation has a general N-S strike dipping subvertically to the east, with mineral lineations that plunge shallowly to the north. The rocks are highly deformed by left-lateral, ductile shearing and late brittle shearing which is marked by epidote-filled veins. The gneisses have been cut by felsic dikes and pegmatites, some of which predate the ductile shearing event.

The Dod Gneiss has relatively higher Mg numbers, high Ni, Cr, Sr and REE abundances. It has a strong geochemical affinity to mantle-derived sanukitoids (the high Mg, silica-oversaturated) andesites from the Miocene Setouchi belt of Japan. The Dod magmas could have evolved from primary magmas generated by partial melting of LILE enriched, shallow mantle sources. The Dosa Gneiss have lower Mg numbers and trace element abundances, and almost parallel REE patterns compared to the Dod Gneiss. These geochemical features are suggestive of liquid-immiscibility relations between their magmas. The two gneisses have similar Sm/Nd ratios with a range in epsilon Nd (1.4 to -3.4, Fig.2).

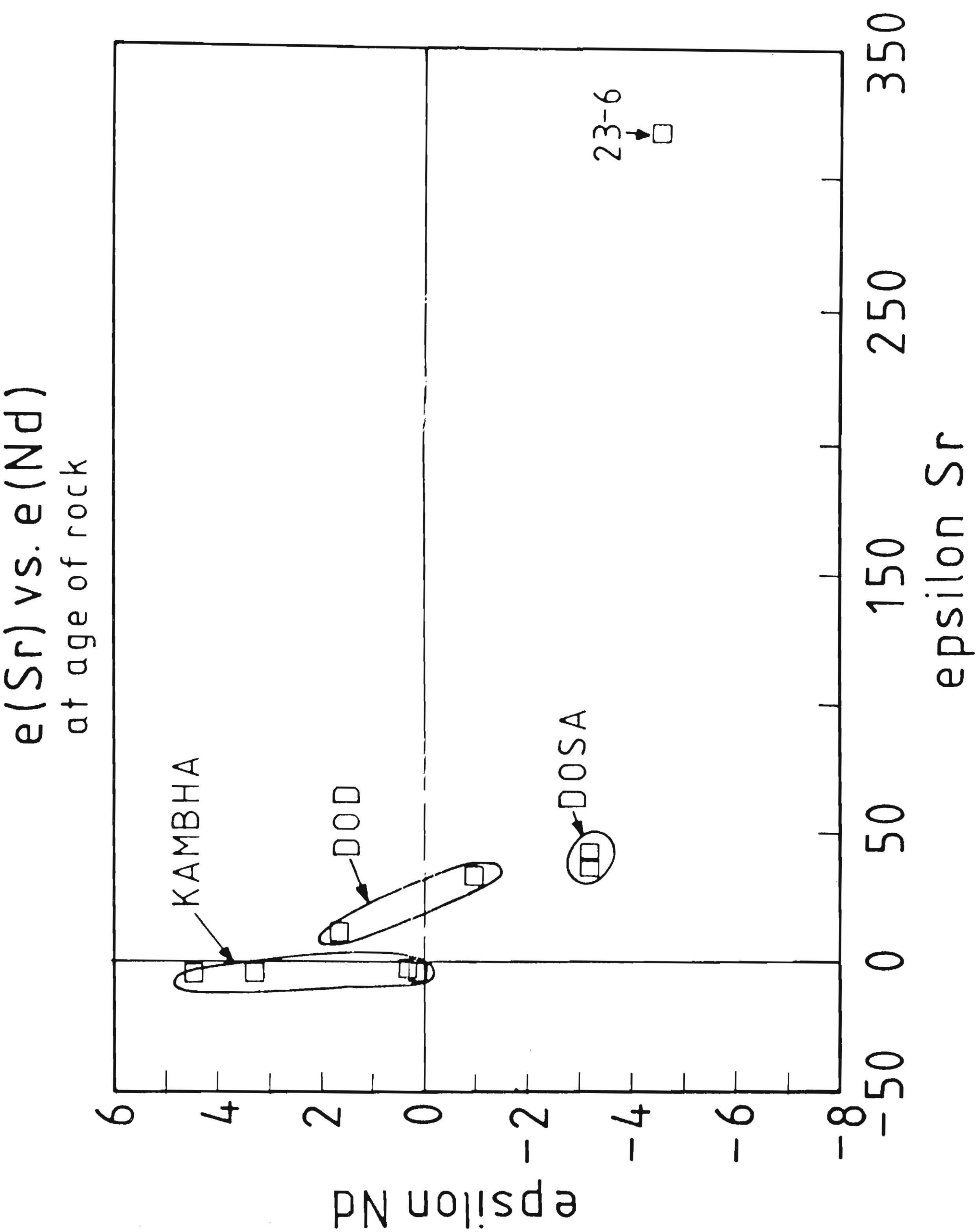


Figure 2. Epsilon Sr versus epsilon Nd diagram for the major granitic gneisses around the belt. Note the difference between the Kambha and Dosa gneisses present on the east and the west side of the belt respectively, which are otherwise similar in their elemental abundances.

The more felsic Dosa Gneiss has a more negative epsilon Nd (-1.9 and -3.4) at 2600 Ma. These initial Nd isotopic ratios indicate that either the sources of the magmas or magmas themselves were contaminated by an older crust; the more felsic Dosa Gneiss had been contaminated to a greater extent. Such an older crust is represented by samples 23-6 and 36 (Fig.3) which will be seen in Stops 2 and 4, respectively. This interpretation is consistent with K-feldspar Pb data which show mixing between a 2600 Ma mantle like source (Mu = 8) and the Pb from samples 23-6 and 36.

Stop 2 Mudgy's Corner - western margin of the schist belt

Here we see the occurrence of closely associated komatiitic and tholeiitic amphibolites. The komatiitic amphibolites are essentially composed of amphiboles with minor opaques. The tholeiitic type has amphibole and plagioclase and is very schistose. The rocks are fine to medium grained and are locally highly sheared. In the Bodgurki Nallah section, east of the iron formation unit, the komatiite-tholeiite association is seen clearly. Komatiites have variable MgO contents, high Ni and Cr contents, and HREE and Ce depleted REE patterns. Their magmas were derived from LREE depleted sources (epsilon Nd at 2700 varies between +2 and +8) by adiabatic melting, from depths greater than 100 km and temperatures greater than 1500°C, to not more than 20%. Their mantle sources have strong similarities to the sources of present day MORB. The tholeiites are not related to the komatiites either by fractional crystallization or by different extents of melting of similar sources even at different P-T conditions. The tholeiitic magmas were derived from shallower lithospheric mantle sources with similar LREE depleted, and lower U/Pb histories.

The iron formation here is represented by amphibole-bearing quartzite and magnetite-bearing quartzite which are intercalated with amphibolites and graphite schists. In some exposures at least three generations of folds are discernible.

The west side of the iron formation is the contact between the schist belt and the gneisses. The gneisses are highly sheared, and are locally converted to quartz-muscovite schists. Foliation planes are marked by near vertical mineral lineations. Muscovite from a sample here yielded an $^{40}Ar/^{39}Ar$ plateau age of 2420 $\pm$ 12 Ma.

The Banded Gneiss unit here (Sample No.23-6) is the foliated, leucocratic and highly sheared rock. In this particular outcrop, the gneiss however, is not banded. It consists dominantly of feldspars and quartz with minor amounts of biotite. Zircons from this rock are complexly discordant, but yield fractions with $^{207}Pb/^{206}Pb$ ages of 3170 Ma. The highly radiogenic Pb($^{207}Pb/^{204}Pb$ = 17.4, $^{206}Pb/^{204}Pb$ = 18.7) and Sr (e_{Sr} = 318) and T_{CHUR} of 3600 Ma make this rock a good candidate for the containment of the Dod and Dosa magmas, as mentioned at Stop 1.

Stop 3 East side - 2 km east of the schist belt margin

The major rock unit seen here is the granodioritic Kambha Gneiss (Sample No.37). The foliation has a strike of N20°E and dips 60° to the west. The rock has been affected by an early, ductile, left-lateral shearing and a late brittle shearing which is marked by the presence of epidote veins. The ductile shear planes make a small angle with the foliation and dip steeply to the west. The rock is medium to coarse grained, leucocratic and consists of plagioclase, K-feldspar, quartz and subordinate amounts of biotite $\pm$ amphibole. Sphene is a major accessory mineral. Epidote is the common secondary mineral. The gneiss is intruded by two generations of aplitic phases (a grey phase and a leucocratic phase) and at least two generations of pegmatites. The rock has a well fractionated REE pattern from La to Dy without any significant Eu anomaly and a concave upward pattern between Dy and Yb. The rock is about 2532 $\pm$ 3.5 Ma old (zircon U-Pb) and has a cooling age of 2514 Ma (sphene Pb-Pb). It has mantle type Sr, Nd and Pb isotopic characteristics (epsilon Sr -2 to -5, Nd 0 to +4.5, Mu_1 = 8.1, $kappa_1$ = 3.9). The rock looks very similar to the Dosa Gneiss on the west side. They have similar major and trace element chemistry. But their isotopic characteristics and ages are different. Important to note is that we are now only 5 km east of Stop 1, where rocks had an older basement and were cooled at 2553 Ma. Here the gneisses have magmatic ages 20 Ma younger than the cooling age at Stop 1 and show no isotopic evidence of emplacement through, or derivation from, an older basement.

Stop 4 Eastern margin, west of the village Peddapalli

Here we see an agglomeratic version, of the Champion Gneiss. The matrix is fine to medium grained, grey to dark grey, well dipping 45-60° to the west. Mineralogy includes plagioclase, K-feldspar, quartz (opalascent and phenocrystic), hornblende and biotite. Zircon, sphene, apatite and sulfides are the accessory phases. The matrix has major and trace element abundances and REE patterns that are similar to the more primitive Dod Gneiss on the west side.

Here the clasts include cobbles and pebbles of granitic gneisses, amphibolites, iron formation and vein quartz. Granitic clasts are the most abundant type and are in general more rounded. Iron formation occurs as thin, long slivers. The lithology of the clasts are similar to those present on the western side of the schist belt. Discordant zircons from one granite clast have yielded a $^{207}Pb/^{206}Pb$ (minimum) age of 2900 Ma. K-feldspar Pb and whole rock Nd from this granite have very evolved composition (epsilon Nd (2600) = -7.5). Thus, this rock could be a fragment of the basement which apparently contaminated the Dod and Dosa magmas. The Champion Gneiss could be a part of or originally formed on, the west side of the schist belt and could be near surface equivalents of the Dod/Dosa gneisses.

SUMMARY

The Kolar Schist Belt includes tholeiitic and komatiitic rocks which were formed from lithospheric and asthenospheric mantle sources with distinct geochemical characteristics which could be related to different tectonic settings of their magma emplacement. The west-central part of the belt is dominated by mafic rocks whose sources are similar to those of present day MORB. The eastern mafic rocks are similar to ocean island or island arc volcanics in their mantle source characteristics.

The belt is surrounded by predominantly mantle-derived granitoid rocks. However, there are major differences in the geological histories of the gneisses on either side of the Belt. On the west side monzodioritic to granitic gneisses formed between 2632 and 2553Ma and cooled from amphibolite grade conditions at about 2550 Ma. Their magmas were contaminated to varying extents by an older continental basement. A potential contaminant with evolved geochemical characteristics is also present on the west side. The lithological associations and the geological history on the west side are rather similar to those of continental magmatic arc environments (Andean and Sierran arcs).

On the east side of the Belt, the gneisses are uniformly granodioritic, formed from mantle sources at 2532 Ma and cooled at about 2520 Ma. Their magmas were not contaminated by significantly older continental crust.

Thus, the two sides ofthe belt had distinct geological histories until after 2520 Ma. The belt itself includes mafic rocks which were formed at different places and/or at different times. All the rocks could have been brought together by tectonic processes at about 2400 Ma. This assembly of crustal fragments in the vicinity of the Kolar Schist Belt has a style and history similar to those seen in various Phanerozoic accretionary terranes, such as the Mesozoic-Cenozoic North American Cordillera.

GNEISS-CHARNOCKITE TRANSITION

Day 3

January 11, 1988

Time		
0830		Leave Bangalore
1000		Reach Kabbal via Kanakapura (84 km). The route followed is along the eastern margin of the Closepet granite.
1100	Stop 1	Kabbal quarry
1300		Lunch Break
1400		Leave for Channapatna
1500	Stop 2	Yelachipalyam quarry
1600		Leave Yelachipalyam for Bangalore
1800		Reach Bangalore

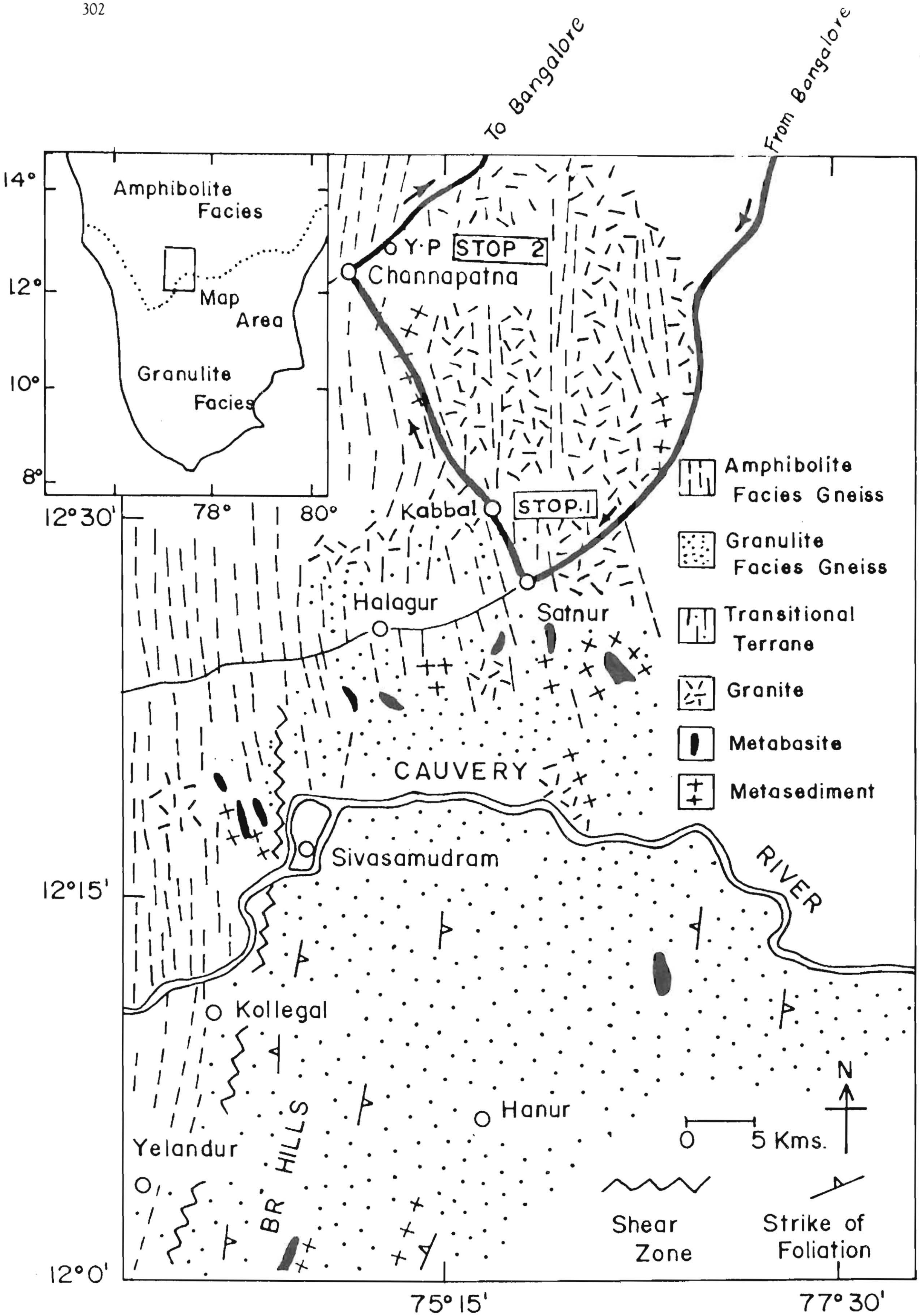


Fig.3: Geological map around Kabbal and Satanur.

/Stop 1/ Kabbal Quarry

Pichamuthu (1953, 1961) was the first to report the striking occurrence of elongate and blotchy charnockite patches overprinting grey Peninsular gneisses at Kabbal Durga quarry. This quarry is located on the flanks of a small pink granite tor, one of several such tors within the Closepet granite belt. The quarry is located at the fort of the hill end almost at the southern tip of the Closepet granite belt (see Fig.3).

Well-foliated grey hornblende-biotite gneiss, intimately mixed with infiltration of pink Closepet granite is the characteristic rock type of the Kabbal quarry. The gneisses show good migmatitic structures, are intensely folded and sheared. General trends are roughly parallel to N 20°E, and are intersected by N 70°E shears. Basic hornblende-biotite layers and boudinaged bands of amphibolite are commonly seen. The gneisses give a date of 2700 Ma (Venkatasubramanian, 1975) by Rb-Sr method and 3400 Ma by U-Pb Zircon data (Buhl, 1987). Younger lamprophyre dykes with brittle deformation can also be seen.

Transformation of the grey foliated granodioritic gneisses to coarse-grained charnockites along shears and foliation planes can be clearly observed (Plate I , Fig.a). The charnockite, chocolate-brown in colour (in contrast to the grey greasy colour of massif charnockite) is coarse-grained. Individual large clots of orthopyroxene can be seen

Plate I, Fig.a Brownish charnockite veins with 'tree' like structures cutting the migmatitic Peninsular gneiss.

Plate I, Fig.b Close up view of the same (Fig.a) showing the development of clots of orthopyroxene in gneiss.

within these blotchy patches (Plate I, Fig.b). The transition from gneiss to charnockite is almost continuous, with coarse-grained charnockite 'veins', transecting or following gneissic foliation. Where charnockite transformation has progressed significantly, the gneissosity is totally obliterated with the development of new foliation, at an angle to the earlier gneissosity. At other places, gneissosity can be traced across the charnockite veins. The margins between the charnockite and the gneisses are diffuse and irregular. The charnockite veins are closely associated with long aplitic veins. The quarry presents a spectacular demonstration of the process connected with the transformation of older gneisses to younger coarse-grained charnockite.

At places, some of the charnockite veins are cut by pink granite veins and at other places, these pink veins have dark margins and are offset by charnockite veins. This suggests that (Closepet) granite veins and charnockite patches formed nearly contemporaneously (Janardhan et al, 1982, Friend 1983).

Association of charnockite with boudinaged metabasic (amphibolites) rocks are also noticed. Unfortunately, these boudinaged basic bodies have been quarried away. Field work during 1982, showed that one metre thick biotite-rich amphibolite had a thick selvedge of px-bearing charnockite on one side only. Aplitic veins cutting the basic bodies had developed charnockite. The entire appearance of the charnockite was that of a hybrid between the metabasite and the aplite. However, no opx or garnet was noticed in the metabasite or at its margins, the whole assemblage had recrystallised to hbe-plag-diopside rock.

The charnockite veins give an age of 2520 Ma (U-Pb of Zircons; Buhl, et al, 1983; Buhl, 1987) (Fig. 4) and 2560 Ma (U-Pb of allanite; Grew and Manton 1984).

In summary, the bulk of the field and radiometric evidence indicate that the charnockite in the areas around Kabbal formed by metamorphism of amphibolite facies Peninsular gneisses at 2540 Ma. The P and T of this metamorphism at Kabbal is around 5-7 Kb at 700-750°C (Hansen et. al, 1984; Stahle et al, 1987). Bulk of the field evidences and the recrystallisation textures strongly indicate that a fluid phase was involved in the formation of charnockite.

Though isochemical metamorphism was first proposed for Kabbal locality by Janardhan et al (1982); Condie et al, (1982), new data (Tables 1 and 2) gathered by Hansen et al, (1987) and Stahle et al, (1987) indicate an open system behaviour of rocks during granulite facies metamorphism. Chemical and modal analyses of the gneiss-charnockite 'pairs' show that the orthopyroxene producing reactions, involved slight losses of CaO, MgO and FeO and gains of SiO_2 and Na_2O. Rb and Y were also depleted (Hansen et al, 1987). Stahle et. al, (1987) further state that extensive replacement of plagioclase by K-feldspar through Na, Ca - K exchange reactions with the ascending carbonic fluids led to strong enrichment in K, Rb, Ba and SiO_2 and to a depletion of Ca.

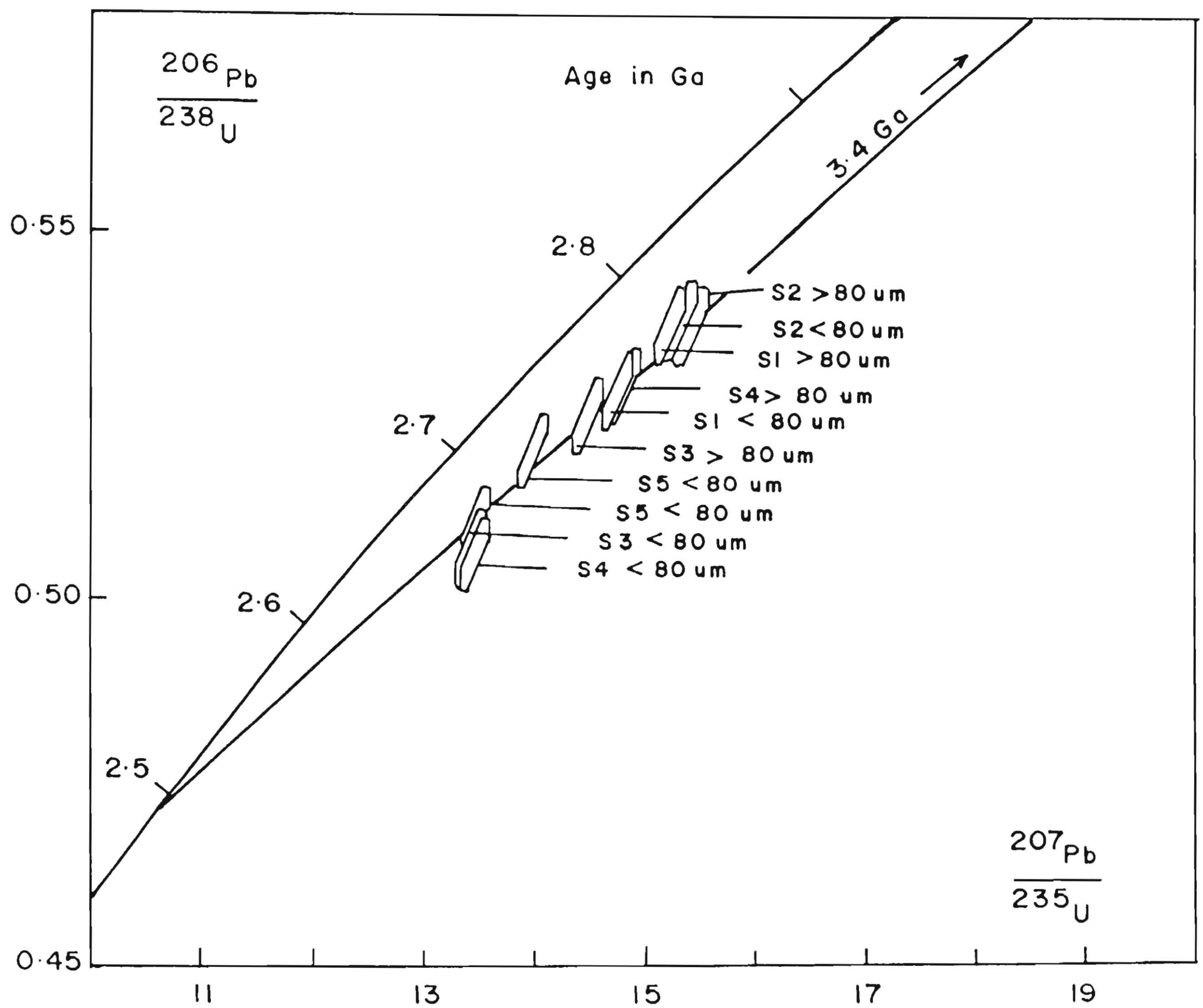


Fig.4 Concordia diagram for U/Zircon ages of charnockites of Kabbal quarry (after Buhl 1987).

Progressive dissolution of hornblende, biotite, magnetite and accessory apatite and zircon resulted in a marked depletion in Fe, Mg, Ti, Zn, V, P and Zr. With advancing charnockitization the moderately fractionated REE patterns give way to strongly fractionated pattern with a positive Eu anomaly. Condie et al, (1982) have demonstrated REE mobility and CO_2 influence on REE elsewhere in the Krishnagiri locality, roughly 200 km SE of Kabbal. Tables 1 and 2 furnish detailed chemical analysis of gneiss and charnockite.

/Stop 2/ Yelachipalayam Quarry

This is a large active quarry 8 km NE of the town of Channapatna and 15 km due north of the Kabbal location. It shows small amount of charnockite (Ziauddin and Yadav 1975). The outcrop is within the Closepet granite terrain and is 20 km further north than previously estimated limits of charnockite. The quarry exposure is a striking combination of grey gneiss and vivid orange-pink granite. The granite is very rich in potash feldspar and appears to be metasomatic, as evidenced by large pinkish porphyroblasts here and there in the gray gneiss with continuous gradations to homogeneous coarse granite, perched remnants of gray trondhjemitic biotite gneiss in a sea of pink granite which show no evidence of dislocation or rotation but which maintain the foliation trends of the local gray gneisses, and near absence of mafic phases in the granite. The charnockite is a dark, very coarse-grained rock found in a few places bordering basic lenses and as veins within metabasites.

Metasomatic alteration of basic lenses is dramatic and varied. Most have selvedges of coarse biotite. Many have plagioclase-rich veins running through them, some with quartz and orthopyroxene, constituting intermediate charnockite. Most commonly, the metabasite adjacent to plagioclase or charnockite vein is converted from a hornblende-andesine rock to an orthopyroxene-andesine-quartz strip about a centimetre wide. Finally, some basic rocks which have been first heavily altered to biotite show abundant coarse lavender garnets replacing biotite. This process possibly gives rise to a curious plagioclase-quartz-garnet rock free of biotite which was found in a few places, some times apparently as attenuated trails of altered metabasites. Another possible explanation of the garnet-plagioclase-quartz rocks is that they are restites of partial melting of trondhjemitic gneiss.

There is thus evidence for occurrence of several metamorphis events:

(1) Emplacement of metasomatic granite and production of biotite in metabasites.

(2) Production of charnockite in gneisses and basic granulite in hornblendic lenses. The rarity of charnockite precludes definition of the time relations relative to granite. However, the major element composition of charnockite is almost linear between gray gneiss and pink granite. This is evidence for the near-contemporaneity of metasomatic granite and charnockite.

(3) Removal of K and H_2O from some biotite-rich rocks leaving garnet-rich residues. It is possible that these components were removed in anatectic melts, rather than metasomatic fluids.

(4) Low temperature production of albite and epidote in plagioclase veins, emplacement of calcite in all rocks, and probably, degradation of orthopyroxene in charnockite to chlorite, creating the characteristic dark coloration.

Table I

Close-pair rock analyses of graygneiss (*GN*) and charnockite (*CH*). Kabbal-type localities

	Kabbal, Karnataka										Waraddana S.L.		Udadigana S.L.	
	1		2		3		4		5		6		7	
	3-1A CH	*3-1B* GN	*3-1A* CH	*3-1B* GN	*3-1A* CH	*3-1B* GN	*3-9A* CH	*3-9B* GN	*4S4-1A* CH	*4S4-1B* GN	*D4-03* CH	*D4-03* GN	*D4-K1* CH	*D4-K1* GN
Wt%														
SiO_2	71.4	68.4	71.8	71.4	71.4	68.7	70.7	69.6	73.9	73.6	69.3	68.4	69.2	68.0
TiO_2	0.49	0.62	0.59	0.60	0.54	0.61	0.53	0.54	0.29	0.44	0.50	0.62	0.41	0.51
Al_2O_3	13.7	13.6	14.5	14.0	13.6	13.6	13.4	13.2	12.9	13.1	14.4	14.5	14.9	14.9
Fe_2O_3	3.13	3.98	3.94	3.92	3.54	4.41	4.04	3.93	2.87	3.25	3.17	4.02	2.80	3.48
MgO	0.79	0.77	0.85	0.89	0.56	0.82	0.67	0.71	0.43	0.68	0.69	0.99	0.63	0.97
CaO	1.95	2.44	2.34	2.52	2.14	2.53	2.24	2.34	1.73	2.16	2.31	2.59	2.13	2.42
MnO	0.06	0.06	0.08	0.06	0.07	0.07	0.08	0.07	0.05	0.04	0.07	0.06	0.05	0.05
Na_2O	3.76	3.65	3.94	3.50	4.14	3.86	4.15	3.94	3.46	3.64	3.74	3.50	3.67	3.67
K_2O	3.67	3.31	2.88	3.52	3.35	3.71	3.44	3.50	3.89	3.22	4.32	4.42	5.09	4.90
P_2O_5	0.12	0.17	0.15	0.17	0.14	0.17	0.03	0.02	0.09	0.15	0.17	0.20	0.14	0.18
CO_2	0.1	0.1			0.0	0.0	0.0	0.0			0.2	0.2	0.1	0.1
S	0.0	0.0									0.01	0.01	0.01	0.01
L.O.I.	0.47	0.31	0.17	0.14	0.23	0.00	0.54	0.08	0.44	0.08	0.77	0.47	0.39	0.31
ppm														
Rb	60	70	71	3	100	110	110	110	98	93	130	150	180	180
Sr	110	130	147	156	190	170	140	150	132	128	330	310	410	410
Zr	230	310	268	274	290	310	320	330	150	116	260	250	210	250
Nb			25	20	30	30	30	30	8	10	20	30	10	20
Y			28	70	10	70	30	60	18	40	20	20	< 10	20
F	470	130									350	820	500	800
Cl	95	120									< 50	50	< 50	50
U	1.0	1.4	0.9	1.1	1.1	1.8	1.7	1.5	0.7	0.4	1.2	2.1	1.9	1.2
Th	15	15	15	12	8	12	27	18	17	1.1	26	18	30	20

Analyses 1, 3, 4, 6, 7 by X-ray Assay Labs. Analysis 2 by present authors at Franklin and Marshall College. Analyses 5 from Allen et al. (1985)

Data from Hansen et al (1987)

Table II

Major, trace, rare earth element contents and whole rock $\delta^{18}O$ values of the 2 m rock profile

	1·1 Gn	1·2 Ch	2·1 Gn	3·1 Peg	3·2 Gn	4·1 Gn	4·2 Peg	4·3 Gn	5·1 Gn	5·2 Peg	5·3 Gn	6·1 Ch	6·2 Ch	6·3 Gn	6·4 Ch
SiO_2	65·6	75·7	68·8	74·5	64·9	70·1	75·7	70·3	69·4	72·8	71·9	77·0	73·8	72·0	71·5
TiO_2	0·83	0·35	0·83	0·33	1·25	0·69	0·19	0·75	0·78	0·33	0·61	0·25	0·34	0·57	0·59
Al_2O_3	15·1	12·6	13·7	13·4	14·0	13·5	11·3	13·8	13·6	13·2	13·3	12·7	12·4	13·5	13·6
Fe_2O_3	6·03	1·46	5·44	2·15	7·66	4·67	1·75	4·66	5·05	2·39	3·98	1·71	2·29	3·65	3·90
MnO	0·10	0·17	0·11	0·03	0·13	0·07	0·17	0·06	0·09	0·04	0·05	0·04	0·05	0·05	0·06
MgO	1·61	0·39	1·23	0·62	1·67	0·95	0·35	0·99	1·07	0·62	0·88	0·29	0·44	0·87	0·80
CaO	4·17	1·51	3·36	1·81	4·14	2·73	0·73	2·85	2·97	1·75	2·44	1·27	1·67	2·45	2·29
Na_2O	4·43	3·37	3·57	2·61	4·03	3·48	2·42	3·31	3·25	2·79	3·15	3·16	3·30	3·22	3·31
K_2O	1·75	4·45	2·45	4·59	1·44	3·24	5·79	2·94	3·15	4·52	3·60	4·97	4·43	3·30	3·22
P_2O_5	0·26	0·05	0·21	0·09	0·32	0·18	0·03	0·17	0·20	0·09	0·15	0·06	0·09	0·14	0·14
Σ	99·88	100·05	99·70	100·13	99·54	99·61	98·43	99·83	99·56	98·53	100·06	101·45	98·81	99·75	99·41
Rb	32	120	55	108	42	68	153	77	58	96	95	111	104	99	68
Sr	142	140	154	148	121	151	139	140	141	148	148	149	151	139	143
Ba	215	806	536	793	283	467	987	474	526	801	560	872	783	528	562
Zr	359	174	321	184	434	280	141	185	310	202	245	183	197	230	249
V	96	22	78	25	141	78	6	75	71	24	57	13	26	45	56
Co	13	—	8	—	13	7	—	8	11	3	10	—	—	3	8
Ni	24	6	36	17	30	6	42	17	20	—	22	—	14	16	—
Zn	84	24	82	28	118	72	25	64	73	41	57	18	38	52	74
La	56	60	75	29	67	65	45	60	68	65	69	56	56	66	63
Ce	133	97	137	46	120	110	72	110	120	101	117	85	89	110	104
Nd	64	25	60	18	69	41	20	47	55	30	48	25	34	46	37
Sm	17·6	3·5	11·9	3·9	16	2·3	2·3	9·8	10·8	4·8	9·7	3·3	6·3	8·3	6·2
Eu	1·7	1·1	1·6	1·4	1·7	1·5	1·4	1·6	1·2	1·4	1·3	1·3	1·3	1·4	1·4
Tb	3·0	0·5	2·76	0·84	3·8	1·22	0·62	1·44	1·97	0·62	1·41	—	0·72	1·2	0·7
Dy	17·3	1·5	15·1	4·3	18·1	7·7	1·4	8·45	11·6	2·8	8·4	1·2	4·8	6·8	3·6
Ho	3·1	—	3·2	0·7	3·7	1·3	—	1·37	2·11	0·33	1·43	0·22	0·7	0·6	0·6
Er	9·0	0·9	10·7	2·3	10·7	3·9	0·9	4·2	7·4	1·5	4·6	0·64	2·4	4·1	2·1
Yb	6·4	0·7	8·6	1·7	8·6	0·6	0·61	3·1	5·8	1·2	3·6	0·6	1·7	1·6	1·6
Lu	0·9	—	1·4	0·3	1·2	0·45	0·1	0·46	0·86	0·2	0·5	0·14	0·25	0·4	0·34
Y	72	6	84	21	95	6		—	—	—	—	—	20	18	17
$\delta^{18}O$	7·0	7·6	7·15	7·3	6·9	7·55	7·7	7·3	7·4	7·5	7·2	7·3	7·5	7·2	7·3

Data from Stahle et. al., 1987

Table II continued

	7-1 Gn	7-2 Peg	7-3 Ch	8-1 Ch	8-2 Gn	8-3 Ch	9-1 Ch	11-1 Ch	11-2 Ch	Average gneisses (n = 10)	Average charnockites (n = 10)	Average pegm. charn. (n = 4)
SiO_2	73·0	75·9	72·3	74·7	68·7	75·7	75·6	73·2	72·0	69·5 ± 2·64	74·1 ± 1·87	74·4 ± 1·42
TiO_2	0·51	0·21	0·55	0·24	0·86	0·37	0·35	0·57	0·55	0·77 ± 0·21	0·42 ± 0·13	0·27 ± 0·07
Al_2O_3	13·1	12·2	13·8	13·5	13·9	13·0	12·9	12·6	13·0	13·8 ± 0·55	13·0 ± 0·47	12·5 ± 0·97
Fe_2O_3*	3·53	1·56	2·74	0·95	5·52	1·97	1·46	3·40	3·07	5·02 ± 1·24	2·30 ± 0·96	1·96 ± 0·38
MnO	0·06	0·05	0·18	0·03	0·12	0·03	0·03	0·06	0·06	0·08 ± 0·03	0·07 ± 0·05	0·07 ± 0·06
MgO	0·82	0·27	0·71	0·47	0·94	0·52	0·53	0·69	0·80	1·10 ± 0·33	0·56 ± 0·18	0·47 ± 0·18
CaO	2·32	1·30	2·13	1·29	3·25	1·49	1·52	1·75	2·44	3·07 ± 0·66	1·74 ± 0·41	1·40 ± 0·50
Na_2O	2·86	2·98	3·83	2·37	4·53	2·86	2·47	3·32	3·87	3·67 ± 0·57	3·19 ± 0·50	2·70 ± 0·24
K_2O	3·59	4·52	3·62	5·36	1·37	4·40	4·56	4·74	2·41	2·68 ± 0·83	4·22 ± 0·88	4·86 ± 0·62
P_2O_5	0·13	0·05	0·16	0·03	0·23	0·07	0·09	0·12	0·14	0·20 ± 0·07	0·10 ± 0·04	0·07 ± 0·03
Σ	99·92	99·04	100·02	98·94	99·42	100·41	99·51	100·45	98·34	99·88	99·68	99·0
Rb	79	119	110	130	40	102	103	118	59	64 ± 23	102 ± 22	119 ± 18
Sr	132	156	157	154	143	151	153	141	148	141 ± 10	149 ± 6	148 ± 7
Ba	534	844	573	899	324	756	794	748	422	445 ± 124	722 ± 152	856 ± 90
Zr	200	165	234	135	334	178	165	253	278	300 ± 68	205 ± 46	173 ± 26
V	41	9	48	14	100	27	18	47	51	78 ± 29	32 ± 17	16 ± 10
Co	9	7	2	—	8	3	9	3	5	9 ± 3	5 ± 3	5 ± 3
Ni	49	33	19	8	—	—	23	21	6	22 ± 13	14 ± 7	31 ± 13
Zn	51	26	51	17	85	27	15	49	50	74 ± 20	32 ± 17	30 ± 7·5
La	36	37	70	39	74	41	65	76	66	64	59	44
Ce	70	59	114	65	120	67	95	108	99	115	92	70
Nd	32	17	33	18	42	40	26	33	31	50	30	19
Sm	8·4	2·5	5·2	2·3	7·3	2·6	4·1	5·0	4·6	10·2	4.3	3.4
Eu	1·5	1·35	1·3	1·2	1·0	1·15	1·3	1·2	1·3	1·45	1·26	1·4
Tb	1·5	0·6	0·96	0·52	0·99	0·44	0·4	0·9	0·8	1·93	0·66	0·67
Dy	7·6	1·2	2·8	0·9	4·2	1·3	1·7	3·0	2·6	10·5	2·34	2·43
Ho	1·4	—	0·45	—	0·61	—	—	0·39	0·38	1·88	0·46	0·51
Er	4·7	1·0	1·6	0·7	2·1	0·8	0·8	1·5	1·4	6·15	1·28	1·42
Yb	3·1	0·6	1·25	0·46	1·8	0·6	0·7	1·31	0·95	4·32	1·0	1·0
Y	0·5	0·12	0·23	—	0·33	—	—	0·25	0·19	0·70	0·23	0·18
Y	32	5	11	4	21	6	7	13	12	52	10	11
$\delta^{18}O$	7·2	7·6	7·35	7·6	7·25	7·7	7·6	7·5	7·35	7·21 ± 0·18	7·48 ± 0·15	7·53 ± 0·17

PENINSULAR GNEISS AND CLOSEPET GRANITE

Day 4

January 12, 1988

Guide: E.B.Sugavanam and K.T.Vidyadharan

Time		
0830		Leave Bangalore
0900	Stop 1	Uttarahalli: Peninsular gneiss and agmatite. Peninsular gneiss quarry, Uttarahalli.
1000		Leave for Ramanagaram
1030	Stop 2	Closepet granite quarry.
1130		Leave for Ammayyanhalli.

Guide: M. Jayananda

1200	Stop 3	Ammayyanhalli quarry - Internal structure of Closepet granite.
1300	Stop 4	Porphyritic granite with enclaves of metatexites.
1330	Stop 5	Albitites.
1430	Stop 6	Brick red rocks.
1500		Leave for Mysore.

Day 4

January 12, 1988

PENINSULAR GNEISS - CLOSEPET GRANITE

Guide: E.B.Sugavanam

The quarry located at 5 km south-west of Bangalore along the road to Kengeri shows the variegated nature of Peninsular Gneissic Complex and its involvement in different tectonic and igneous events.

Stop 1. Peninsular Gneiss: Uttarahalli Quarry.

About 1 km west of Uttarahalli village, along the north side of road to Kengeri, the low mounds expose Peninsular gneiss with larger agmatitic blocks of mafic rocks of varying dimensions in random orientation. These mafic blocks are of gabbroic to amphibolitic composition and show various stages of digestion and assimilation by granitic material. Well layered 'Stromatic' gneisses of diorite to granodiorite composition border the margins of these 'restite' blocks of mafic rocks. Much younger coarse granite and pegmatoidal veins, rich in pink potash feldspar cut across the gneissic fabric of the Peninsular gneiss.

Roughly ½ km west of the above, where road turns due south, along the western side of the road, a large coarse grained homophanous pink granite is located in

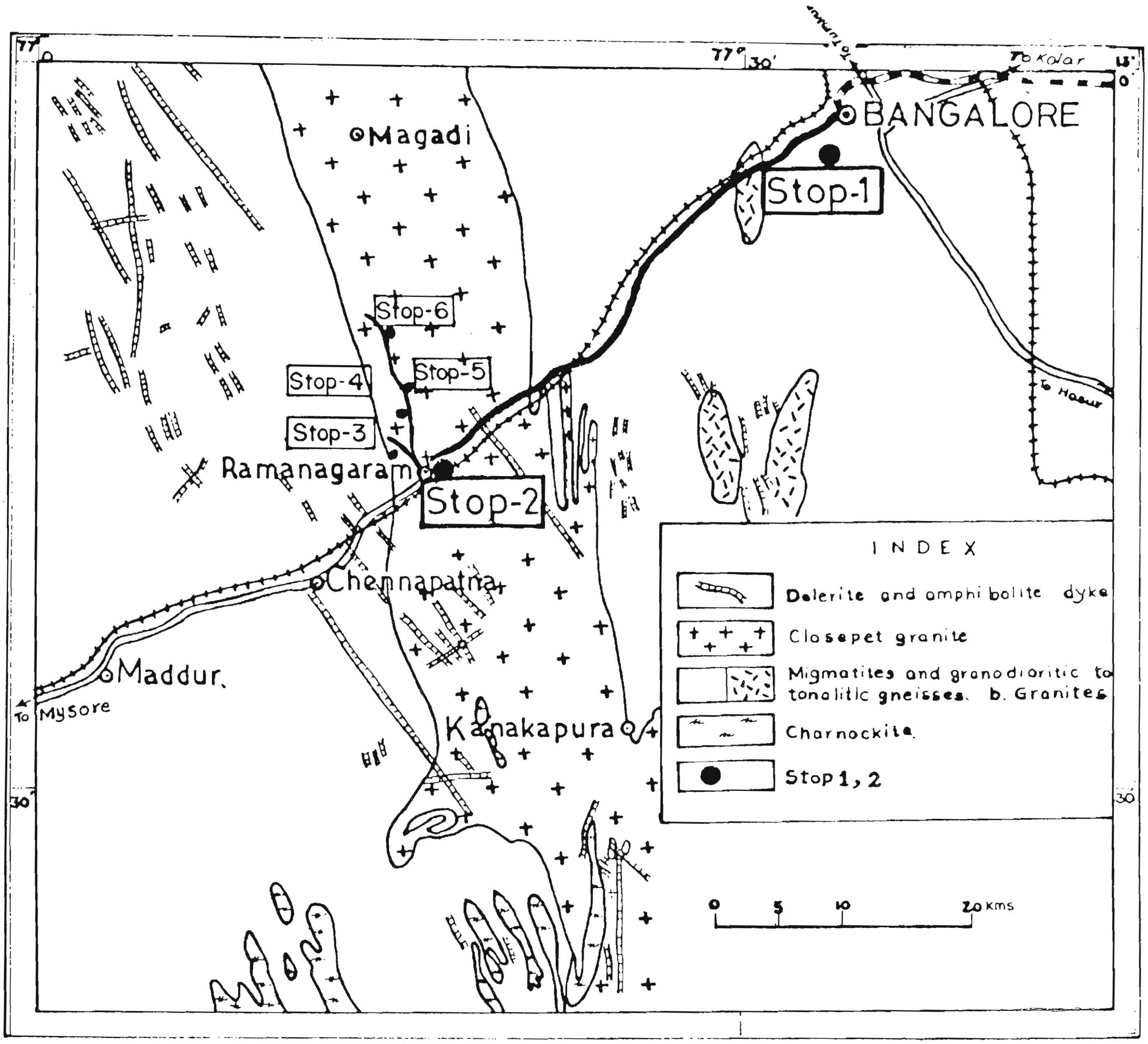


Figure 5. Sketch map showing Closepet Granite-Peninsular gneiss relation.

NNE-SSW alignment. The bouldery outcrops of granite do not exhibit any foliation and deformation and appear to be post-tectonic granite intrusive. It is predominantly quartz and felspar rich with less mafics.

Quarry west of Patalamma temple.

The NE-SW aligned quarry, located west of the temple and south of the road to Kengeri, exposes the different components of Peninsular gneisses and their mutual relationship as well as the effects of different tectonic and igneous events on them(**fig.6**).

Highly contorted dioritic to granodioritic gneiss, rich in mafic minerals (biotite hornblende) forms the dominant unit in which dark mafic enclaves, representing earlier dykes/sills are in various stages of disintegration and assimilation. They are highly contorted and are involved in intense deformation. These gneisses show a highly contorted E-W foliation.

The E-W foliation in the gneisses has been markedly affected by N.10° to 15°E - S.10° to 15°W trending shear folds which are very well exemplified throughout the quarry. The effects of this shear fold are refleeted in

(1) the development of a very well defined axial plane foliation exhibited by preferred orientation of hornblende and biotite grains,

(2) the development of pronounced fracture cleavages and shear planes with formation of epidote veins along these planes,

(3) the emplacement of basic dykes, presently schistose amphibolite in composition, preferentially along the axial planes of the above shear folds,

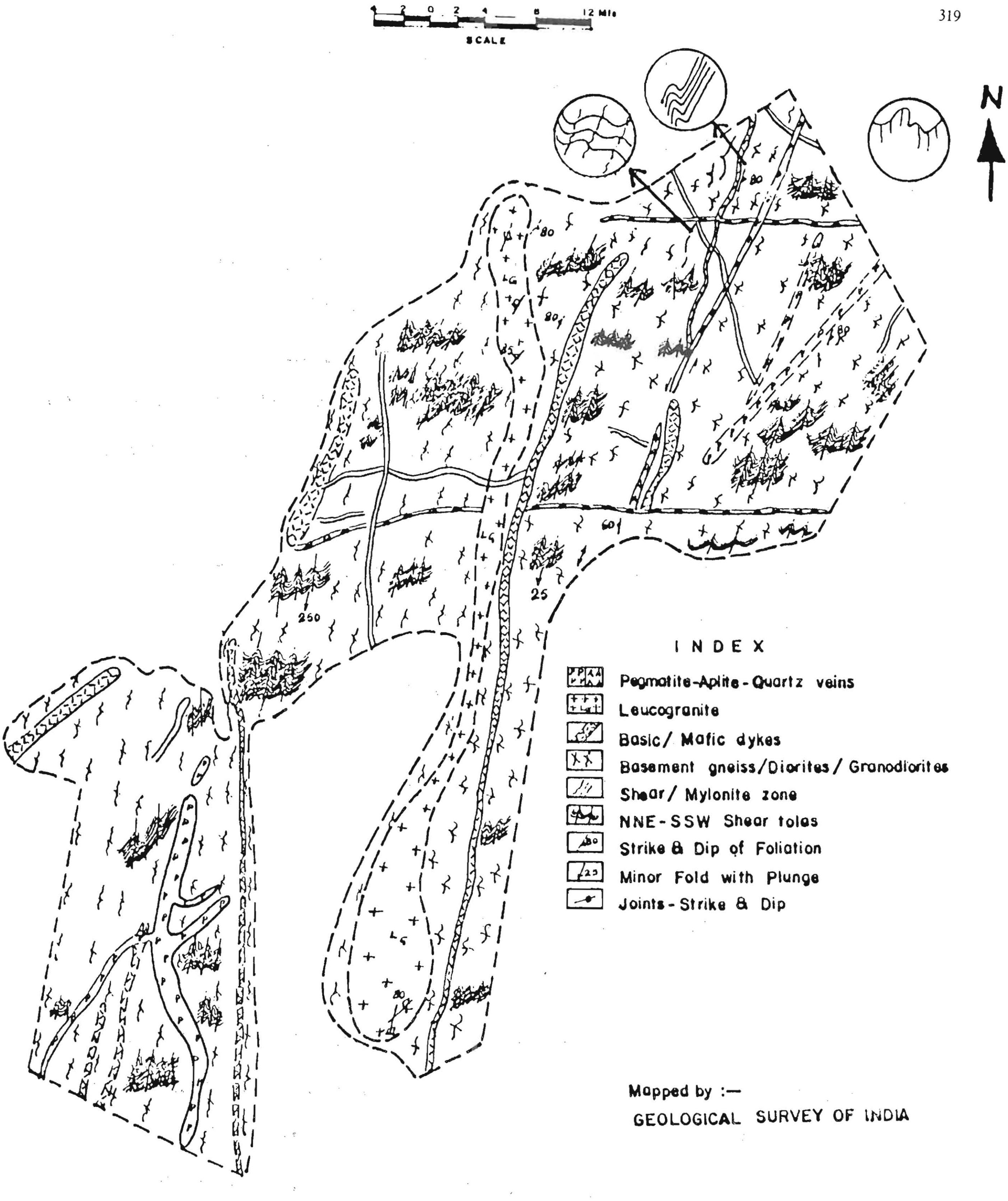


Fig.6 Sketch map of Patalamma quarry, Uttarahalli.

(4) the emplacement of medium to coarse grained leuco granite along NNE-SSW trend,

(5) the emplacement of allanite bearing coarse pegmatites and fine grained aplites along these fractures.

Both sinistral and dextral movements along these shears have been noted.

While the basic dykes and the leuco granite, along the NNE-SSW alignment, show effects of shearing and development of schistosity/foliation, indicating reactivation of the shear planes subsequent to their emplacement, the pegmatite and aplite veins do not show any such effects indicating their post shear emplacement.

Following is the tentative tectonostratigraphy worked out in this quarry:

7. Pegmatite, aplite and quartz vein
6. Leucogranite
5. Basic/mafic dykes (amphibolites)
4. NNE-SSW shear folds
3. E-W foliation
2. Mafic and basic dykes/sills
1. Basement Gneiss (?)

Regionally, the above features in the quarry may represent the superposition of N-S to NNE-SSW "Dharwar trend" on E-W trending basement Peninsular gneiss, resulting in the formation of shears and fractures in N-S to NNE-SSW alignment. These shears facilitated the emplacement of basic dykes as well as younger granites including possibly the Closepet granite.

Stop 2 Ramanagaram Quarry (Closepet granite-Peninsular gneiss relation).

The quarry located, east of 43rd km stone on Bangalore-Mysore highway and 3 km south east of Ramanagaram town lies within the zone of Closepet granite. Here, the relationship between the Peninsular gneiss and the porphyritic phase of Closepet granite, is very well exemplified (**fig.7**).

Very coarse, pink porphyritic granite shows various stages of assimilation of Peninsular gneiss and its mafic enclaves. While the Peninsular gneiss and its mafic components are still recognised as in dependent entities at the western half of the quarry, they are completely homogenised and assimilated and only coarse porphyritic pink granite occupies the eastern part of the quarry. On the west, the well banded and layered migmatitic gneiss has N-S to N.15°E - S.15°W trends with steep (80° to near vertical) dips towards east and is granitic to granodioritic in composition. Coarse pink porphyritic granite veins form lit par lit injections within migmatitic gneiss and often show development of augens of pink felspar up to 3 cms in length along wall-rock contacts.

Dark basic enclaves of varying sizes and shapes, having relict foliation, exhibit evidences of rotation, compression, elongation and assimilation. Larger basic enclaves of dioritic composition show influx of pink quartzofelspathic material and effects of migmatisation.

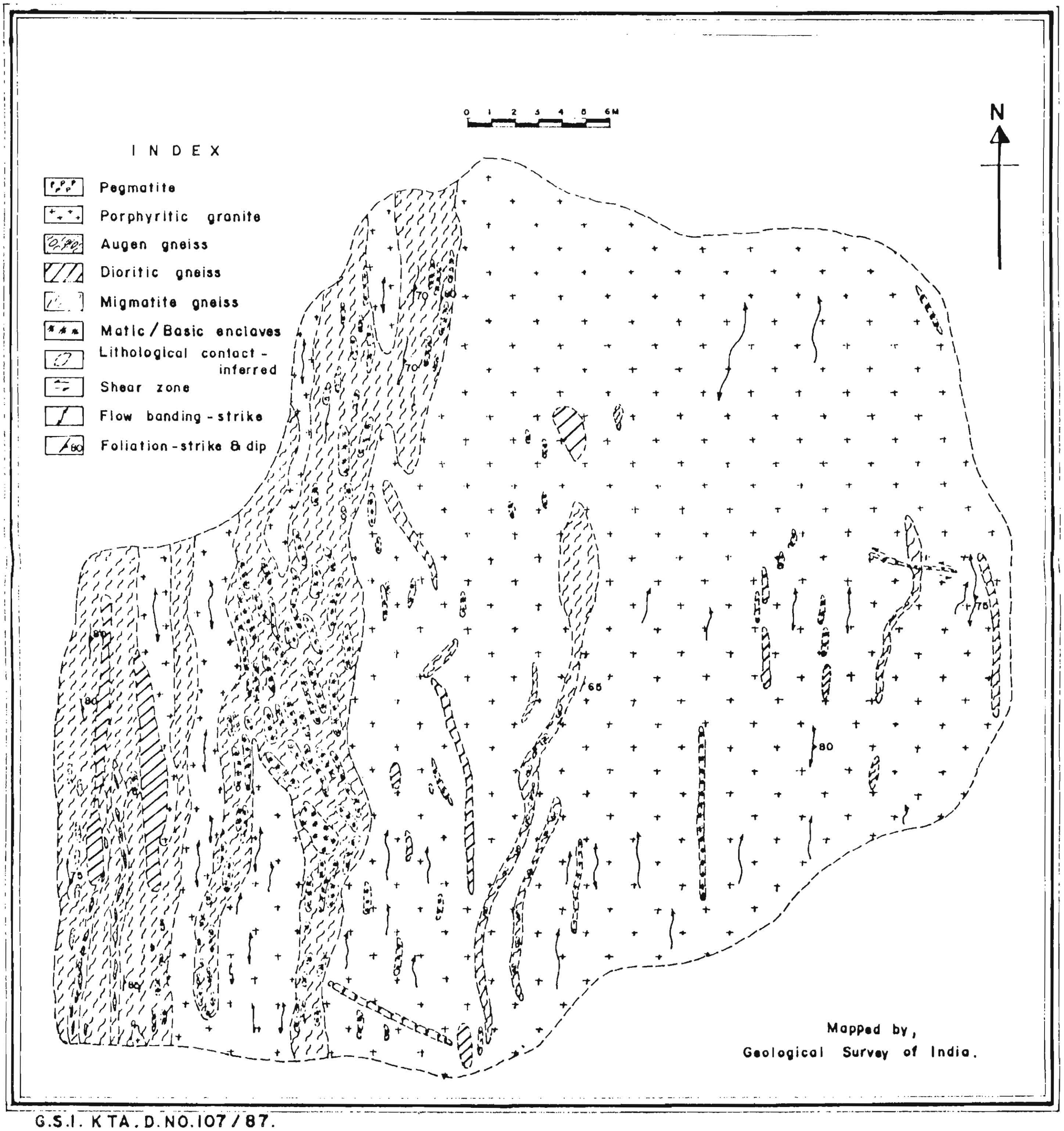


Figure 7. Closepet Granite Quarry, Aparnakallu, Ramanagaram.

Some of the basic enclaves in the north show aureoles of alteration with almost gabbroic to pyroxenite composition at the core.

Except for the effects of elongation and rotation at their contact with mafic enclaves and Peninsular gneiss, the coarse pink porphyritic crystals of felspar varying in size from 2 to 3 cm in length and 2 cm across exhibit pronounced flow foliation with frequent contortions in N-S to NNE-SSW alignment. Most of the feldspar crystals exhibit well preserved Carlsbad twinning. In the quarry cross section, these flow bands show 65° to 80° dips towards east.

Along the eastern half of the quarry, the mafic patches are nearly homogenised forming "nebulites" due to their assimilation by porphyritic granite.

Development of E-W shear and filled by thin pegmatite veins appear to be the only younger tectonic event affecting the porphyritic granite.

The irregular tongues and apophyses of pink porphyritic granite within well banded migmatitic gneiss along the western part of quarry clearly indicates the intrusive nature of the pink porphyritic granite, and it has very little effects of subsequent tectonism or deformation implying the absence of any such events after its emplacement.

Stop 3. Ammayyanahalli quarry - About 2 kms NW of Ramanagaram

An actively working quarry exposes polyphase complex internal structure of the Closepet granite. The earliest phase is the pyroxene-bearing dark grey granite, which is cut by the porphyritic pink granite, both of which, in turn, are cut by an anostomosing network of cross-cutting pink veins. The dark grey granite is foliated, which is defined by the alignment of mafic minerals. The dark grey granite contains gneiss enclaves and basic xenoliths. The porphyritic granite is coarse-grained and occurs as discontinuous sheets. The K-feldspar megacrysts are pink in colour and are roughly aligned. The porphyritic granite contains enclaves of gneiss and dark grey granite. The pink granite is medium grained and contains amphibole crystals probably drived from the gneiss.

Stop 4. Quarry west of 4.8 km stone Ramanagaram-Magadi Road.

Here the quarry exposes predominantly coarse-grained porphyritic pink granite with enclaves of metatexite and gneiss. The K-feldspar megacrysts are pink in colour and are aligned. The matrix is pink grey in colour and the chief mafic phase is amphibole. Biotite schlerien are present in metatexites. The gneiss enclaves are weakly banded and biotite spall off can be observed along the margin. The trend of enclave is N.S.

Stop 5. Albitite (Ramanagaram-Magadi road)

The albitite is an unusual type of rock found along the dyke margin. The albitite is light green, porphyritic with up to 70% of large alkali feldspar megacrysts.

SKETCH MAP OF AMMAYYAMAHALLI QUARRY
(Not to scale)

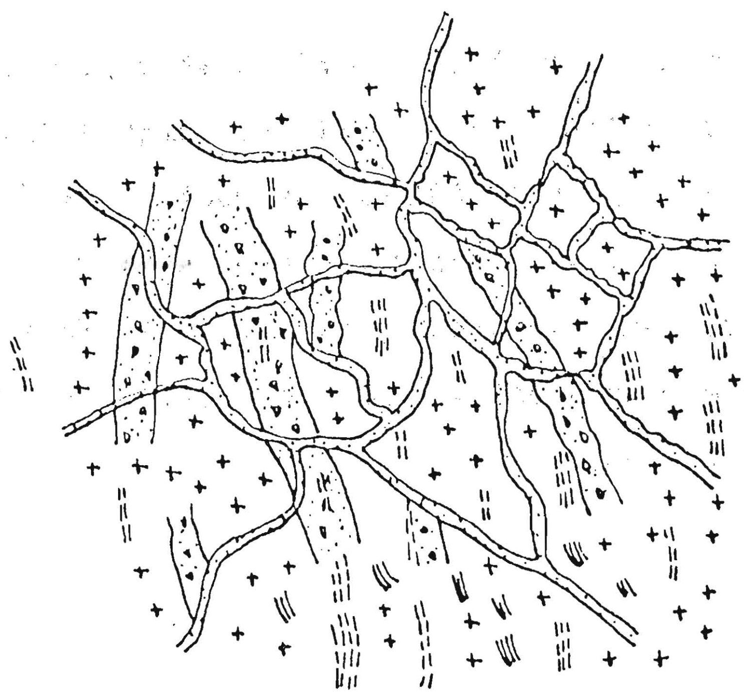


Figure 8.

PENINSULAR GNEISS

DARK GREY GRANITE

PORPHYRITIC PINK GRANITE

EQUIGRANULAR PINK GRANITE.

The megacrysts are white to cream coloured and the matrix green with abundant epidote. A gradual transition from the porphyritic granite from the margin to the centre of the albitite outcrop may be observed.

Stop 5. Brick Red Rocks east of 9.7 km stone Ramanagaram-Magadi road.

Ridges of brick red rock are found at this point. The rock is deep red in colour and consists of large K-feldspar megacrysts constituting up to 80% of the rock. The K-feldspar megacrysts are red in colour and their abundance increases from margin to the centre. Grass green coloured chlorite is abundant in the matrix and a number of epidote veins cuts across the brick red rock.

ANCIENT SUPRACRUSTALS (SARGUR TYPE)

Guides: A.S.Janardhan and C.Srikantappa

Day 6

January 14, 1988

Time		
0830		Leave Mysore
0930		Reach Bettadabidu
0930	Stop 1	Bettadabidu Carbonates, Quartzites and Aluminous Schists.
1030		Leave for Nugu
1200	Stop 2	Archaean BIF amphibolite paragneiss Nugu
1230		Nugu Dam - Lunch Break
1400		Leave for Doddakanya
1600	Stop 3	Doddakanya Magnesite Mines
1700		Leave for Mysore

The days programme is intended to give a general idea of the ancient supracrustal rocks (Sargur type). Best exposures are along canal sections. Only a few typical exposures located close to the road are covered by the day's tour.

Stop 1 Bettadabidu.

Towards the southern most end of Konnainbetta range and at its western margin, a small carbonate band, a part of the main Bettadabidu band, is exposed. This is typical of the carbonates of the ancient supracrustals (See Fig.10). Carbonates show a brownish weathering skin due to appreciable manganese content up to 5%. They are essentially made up of calcite-dolomite-diapside-tremolite± serpentine-talc-phlogopite-graphite. Carbonate band interbanded with amphibolites.

Stop 2.

Before reaching Nugu dam site about a km or so before, brief stop is planned to examine typical pelites exposed around Sargur. These pelites are represented by Sillimanite-Kyanite±Corundam graphite-bearing schists. These schists along with quartzites (kya/silli bearing) and BIF make up the hill ranges which can be seen in the distance. Unfortunately, these are too far away from the main road and difficult of access. Sillimanite-kyanite-graphite bearing schists are profusely intruded by pegmatite veins

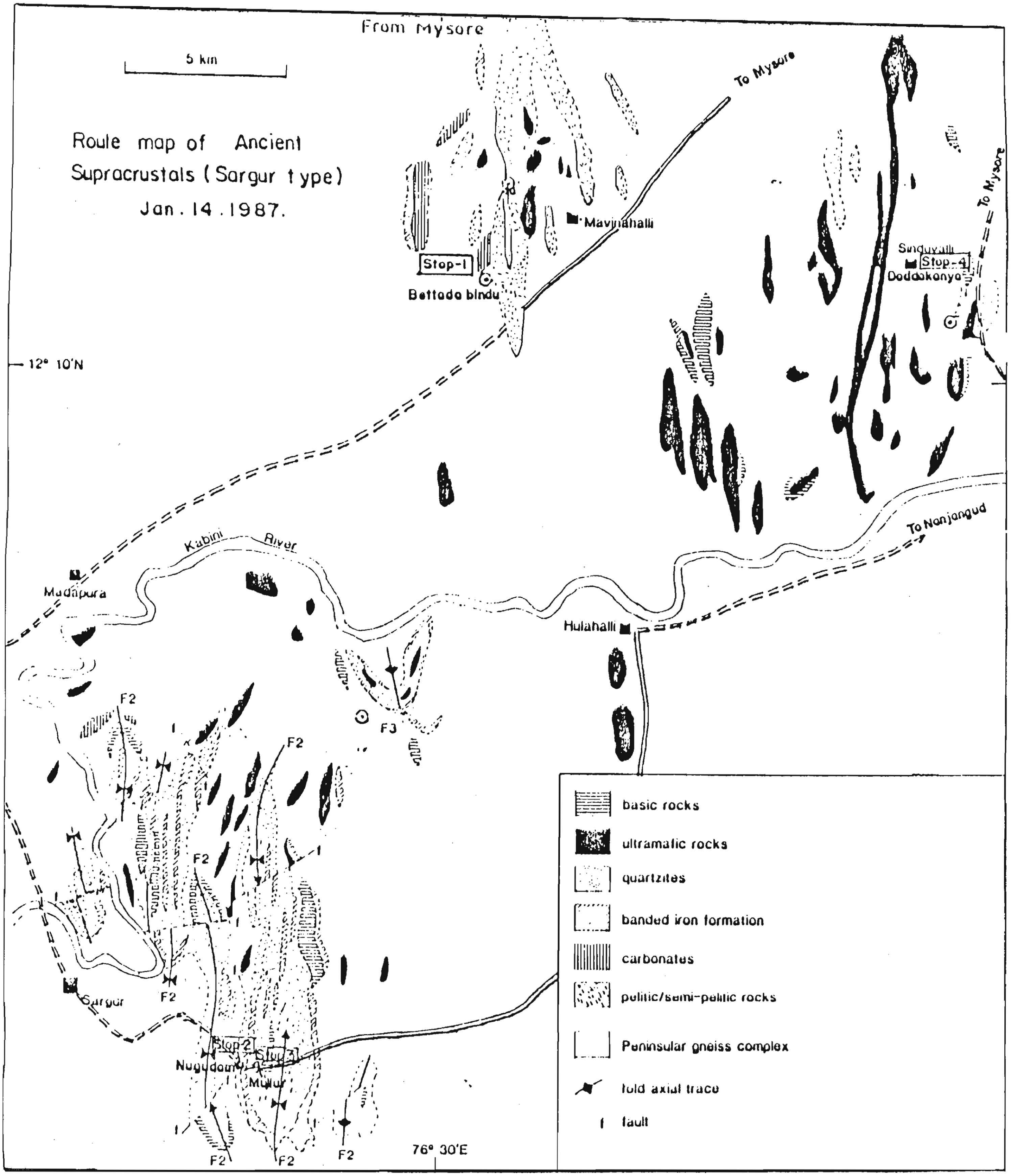


Figure 9. Geological sketch map showing the distribution of ancient supracrustals to the south of Mysore.

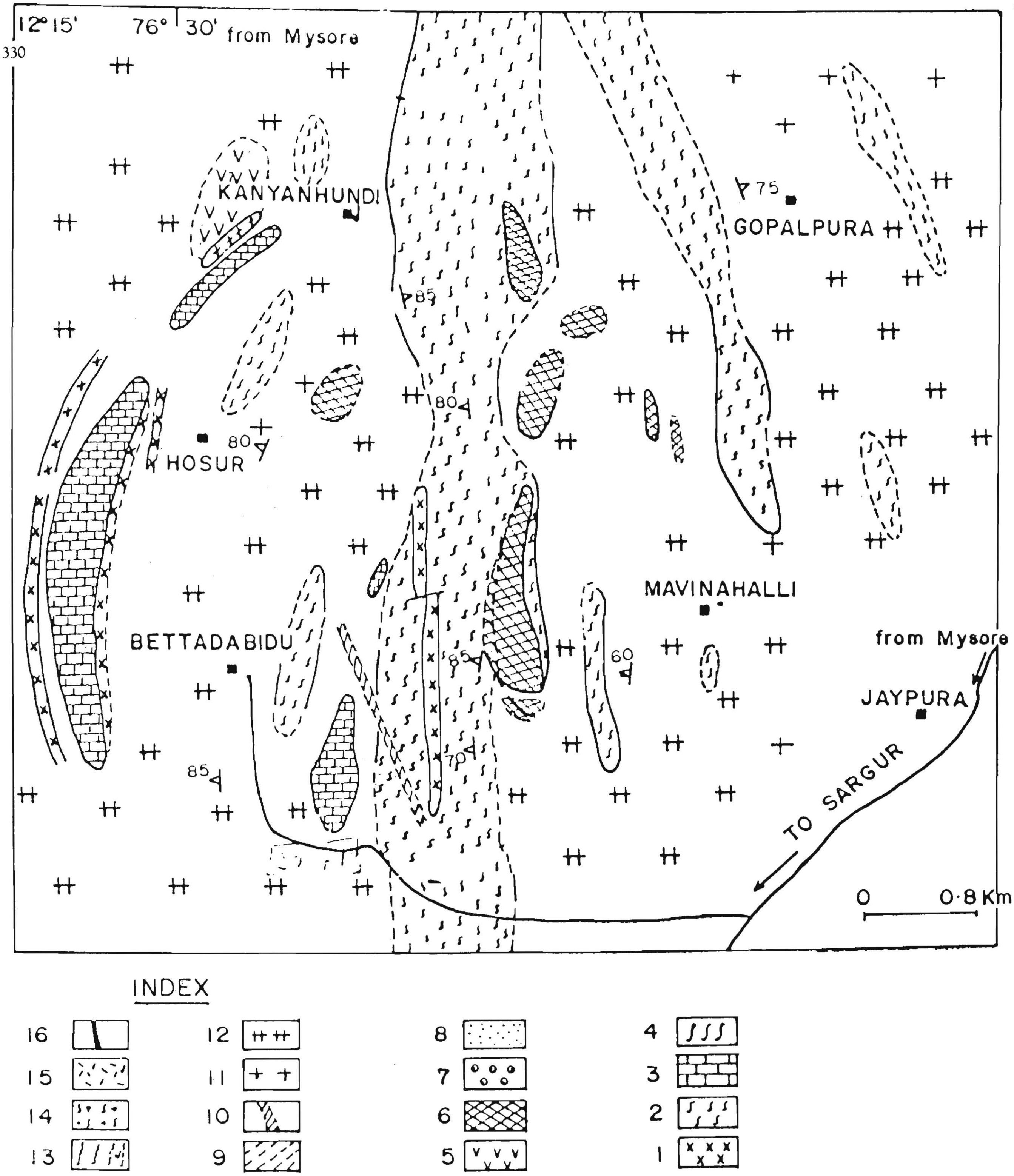


Fig.10: Geological map around Mavinahalli (Srikantappa, 1979).

Explanation for index:-

1. Quartzite (+fuchsite).
2. Pelitic schist.
3. Marble.
4. B.I.F.
5. Amphibolites.
6. Dunite (dominantly harzburgite).
7. Bronzite peridotite.
8. Pyroxenite.

09. Two pyroxene granulite.
10. Hornblendite.
11. Reworked quartzofelspathic gneiss.
12. Migmatite gneiss.
13. Banded hornblende gneiss.
14. Gar+Sill+Biotite gneiss.
15. Granite.
16. Dolerite.

at this locality and a little farther, the same pelites are invaded by ultramafics, which are now highly serpentised.

At the Nugu dam site, a road cutting exposes minor 0.5 m. - 2 m. bands of BIF, interbanded with amphibolites. This is again typical of Sargur terrain. The BIF at this locality is represented by quartz-magnetite-altered orthopyroxene altered granerite and garnet. The amphibolites are cpx-hbe-plag-qz bearing with no orthopyroxene. At the contacts with BIF, garnets develop rather profusely.

Stop 3.

Further north, on the road to Hura/Hullahalli, small quarries of kyanite bearing paragneisses can be seen. These paragneiss are the migmatised products of the Sargur pelites. Often these paragneisses contain knotted enbyred corundam. The kyanites are bluish in contrast to the greyish kyanites of the kyanite-sillimanite-graphite schists ($Al_2O_3 \simeq 54\%$) and contain some chromium. These paragneisses are seen in the plain ground separating the hillocks of Sargur area.

Stop 4. Doddakanya Mines.

The magnesite mine is situated at the southern tip of a linear ultramafic body (Fig.11). This body is essentially made up of serpentinized dunite/harzburgite. Reasonably fresh dunite can be seen in mine excavation. Thin bands of bronzite peridolite and pyroxenite are separated by gneisses. A garnet-sillimanite biotite-feldspar bearing band of gneiss occurs at the border of the ultramafic body. Disseminated chromite is present. The most striking feature is the

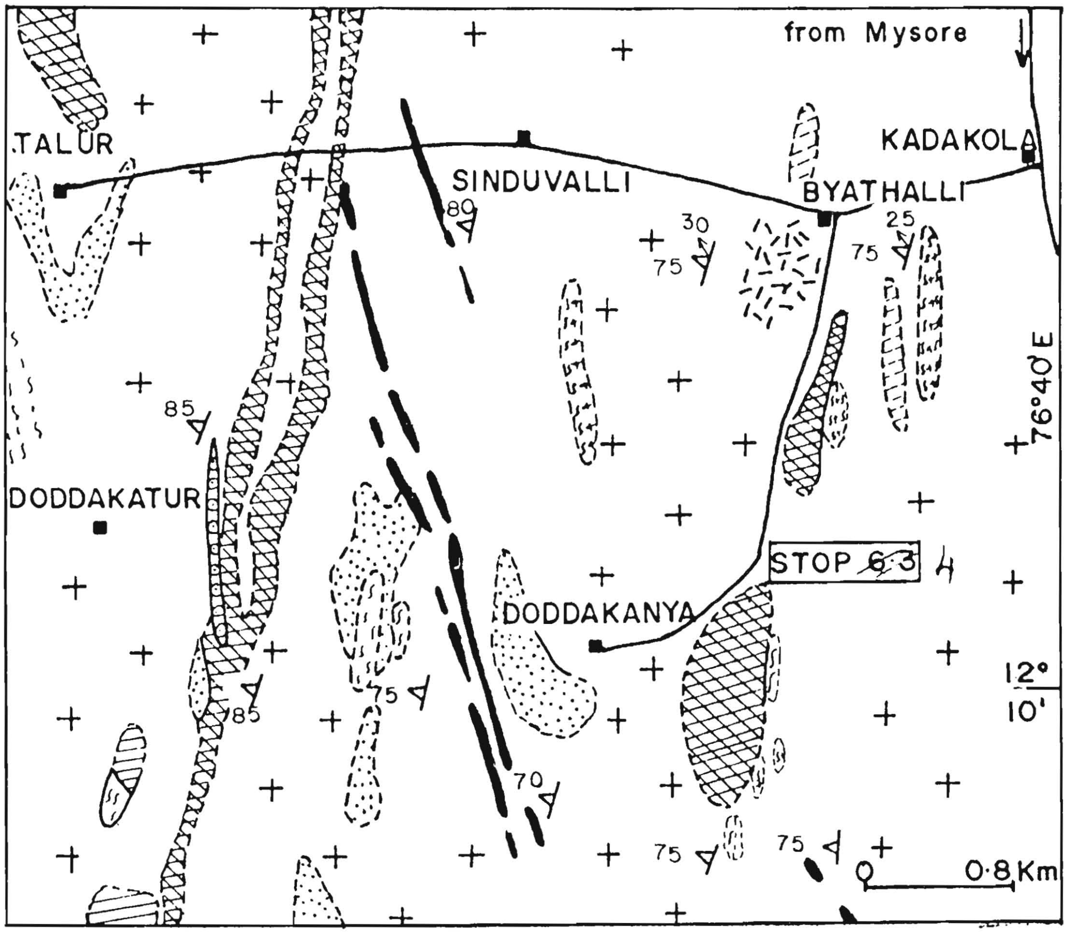


Fig.11 - Geological map around Doddakanya.

occurrence of numerous runs of metabasic dykes, garnet-bearing two-pyroxene granulites cutting the ultramafic. At the contact with serpentinites, the two-pyroxene granulites are transformed to hornblendites.

During mining operations at Doddakanya mines during 1975, an interleaved biotite-bearing gneiss had got exposed. This gneiss at that time had a width of 11 m with garnet-biotite-feldspar-quartz and had got transformed to a well foliated orthopyroxene-plagioclase feldspar (An_{20})-quartz rock. The orthopyroxene had altered to anthophyllite with orthopyroxene preserved only in the core. The entire rock is abundant with rutile and zircon as accessories. The whole body occurred very near the eastern margin of the Doddakanya ultramafic body. Only a part of this body is exposed now.

Doddakanya Magnesite: Ultramafic rocks of Doddakanya are intersected by a branch work of magnesite veins. Magnesite formation is restricted to harzburgite and durite varieties. TISCO has been mining in this locality for the last 30 years. The deposit is a small one and similar deposits are common to the ultramafics of the Sargur belt.

At Doddakanya mines, magnesite mining is restricted to 20 m from the surface and vertical drill holes from the present mining level, 30 m below have proved that the serpentinites are barren of magnesite. Magnesite veins are generally parallel to one another and they commonly show pinch and swell structures. Good quality magnesite and comparatively thicker veins are often found at the contacts of the basic bodies and the serpenitinised rock. Thickness of the veins vary from 1 cm to 3 m. They are poor in silica content ($<4\%$) and this is one of the reasons this deposit is still being mined.

The parallel network of veins, pinch and swell structures and the absence of magnesite below 30 m suggest that magnesite formation is due to circulating meteoric waters.

GUNDLUPET GNEISS, NILGIRI CHARNOCKITES AND MOYAR SHEAR ZONE

Day 7
15 January 1988

Time		Guide: **A.S.Janardhan and C. Srikantappa**
0830		Leave Mysore
0930		Reach Gundlupet (60 km)
0930	**Stop 1**	Examination of gneissic quarry near Gundlupet
1030		Leave Gundlupet to Masanigudi via Teppakadu (34 km)
1130	**Stop 2**	Examination of retrogressed charnockite near Masanigudi (shear zone) Moyar.
1300		Lunch break at Teppakadu
1430		Leave Teppakadu and reach Ooty (hill section) around 1730 hrs (55 km)

Stop 1. Gneissic quarry near Gundlupet

This stop is a spill over of the previous day's trip and has been squeezed in this day's programme, as Gundlupet is on the way to Ooty. The participants will have an opportunity of studying in this quarry typical features of migmatitic grey trondhjemitic gneisses profusely traversed by pink granitic veins. Rb-Sr isochron of the composite gneiss of this quarry along with specimens from similar gneisses in the Terakanambi region, give a metamorphic age of 2850±50 Ma (Janardhan and Vidal, 1982). However, zircons from the grey phase of these gneisses have given U-Pb age of 3300 Ma (Buhl, 1987) (Fig.12). Monazite from the same gneisses give an age of 2505 Ma implying effects of granulite facies metamorphism or of younger granites of Closepet affinities.

The gneisses, termed as Gundlupet gneisses, show typical migmatitic features and contain enclaves of Ancient Supracrustals. Hillock south of the road contains abundant calc-silicate enclaves, whereas in the quarry, one can see amphibolites (garnet-cpx-hbl-plag) occurring as huge enclaves, with the original intrusive nature still preserved. The amphibolite represents basic igneous bodies interbedded with metasediments as at Bettadabidu. This implies that the Supracrustals noticed here are probably older than 3300 Ma.

A small enclave of spessartine garnet-cpx-bearing Mn-horizon is seen in the nullah cutting close to the road. Though nothing definite can be made out from this small occurrence, it only reinforces the argument that Mn-horizons are ubiquitous in the supracrustals of this region.

Return to Mysore-Ooty highway and proceed to Ooty.

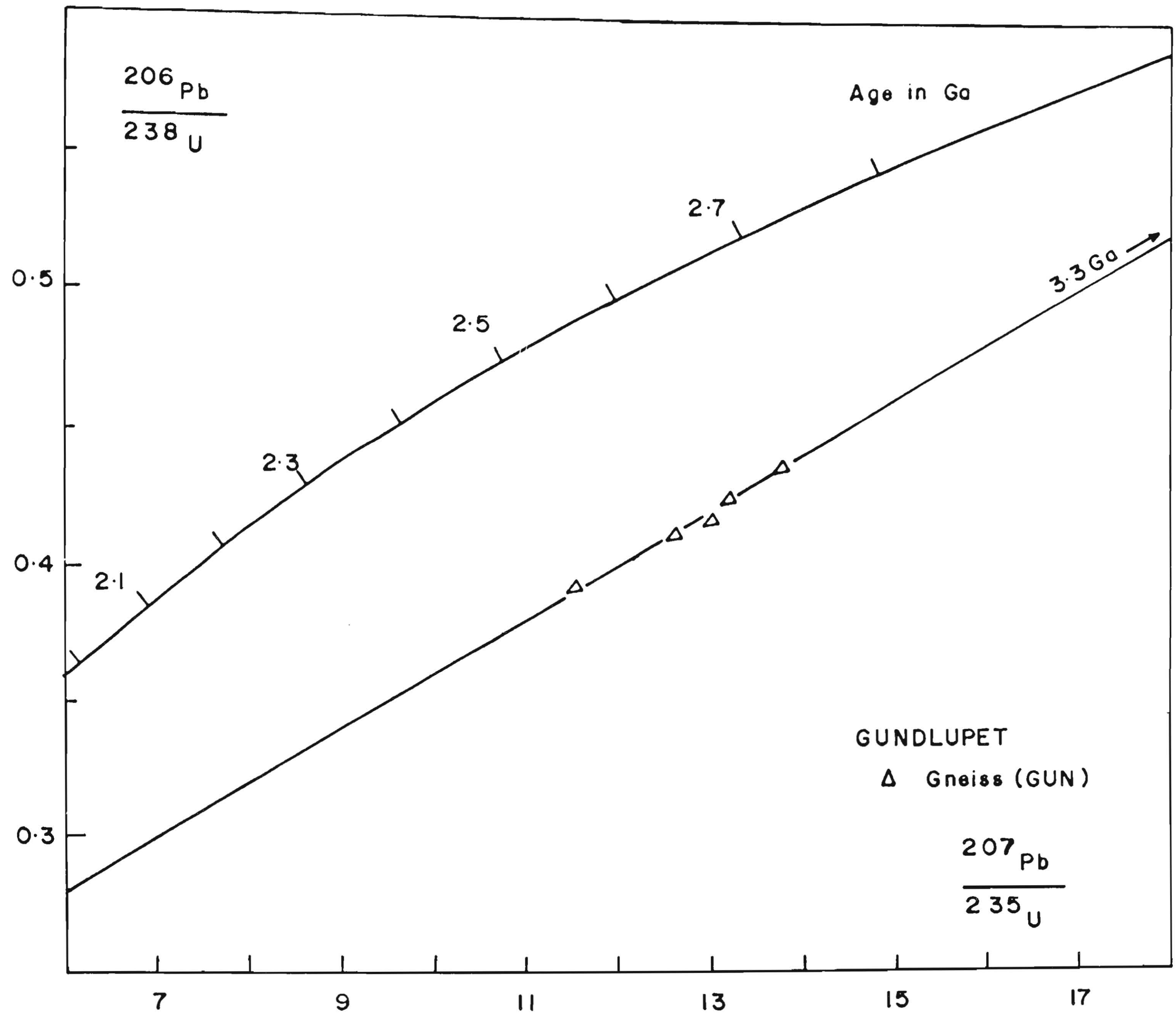


Fig. 12. Concordia diagram for U/Pb Zircon ages for Gundlupet gneiss (after Buhl 1987).

 Stop 2 Masanigudi quarry

This stop is located within the Moyar valley (Fig.13) in a dense forest infested with wild elephants. From here, one can see the abrupt wall of the Nilgiri charnockite massif. This stop is about 6 km east of Teppakadu on the Mysore-Nilgiri highway.

The quarry near Masanigudi exposes various stages of retrogression of massive charnockites. Medium to coarse-grained, garnetiferous charnockite is exposed in the quarry with enclaves of garnetiferous gabbro and pyroxenite. The foliation strikes N 70-80°E with steep dips. Minor, tight isoclinal folds trending N 85°E are observed. In thin sections, charnockite is composed of plag-qtz-opx-gt-bio, exhibiting granoblastic texture. Fluid inclusions in quartz indicate the presence of CO_2-rich inclusions of high density (0.800 g/cm^3).

Two sets of conjugate shears trending N 15°E and N 15°W cross-cut the general foliation. Another set of shear planes trending N 80°E is noticed. Development of highly irregular, bleached and retrogressed zone is observed all along these shear planes. The width of the bleached zone varies from few cm to a maximum of 2 - 3 m. Thin section study of bleached zones show breakdown of garnet to give rise to symplectitic intergrowth of garnet-quartz and replacement of orthopyroxene by hornblende and biotite. Fluid inclusion studies across the bleached zones, suggest a change in fluid composition from mixed CO_2-H_2O to H_2O-rich inclusions. This suggests that retrogression of charnockites was caused by influx of water along shear zones.

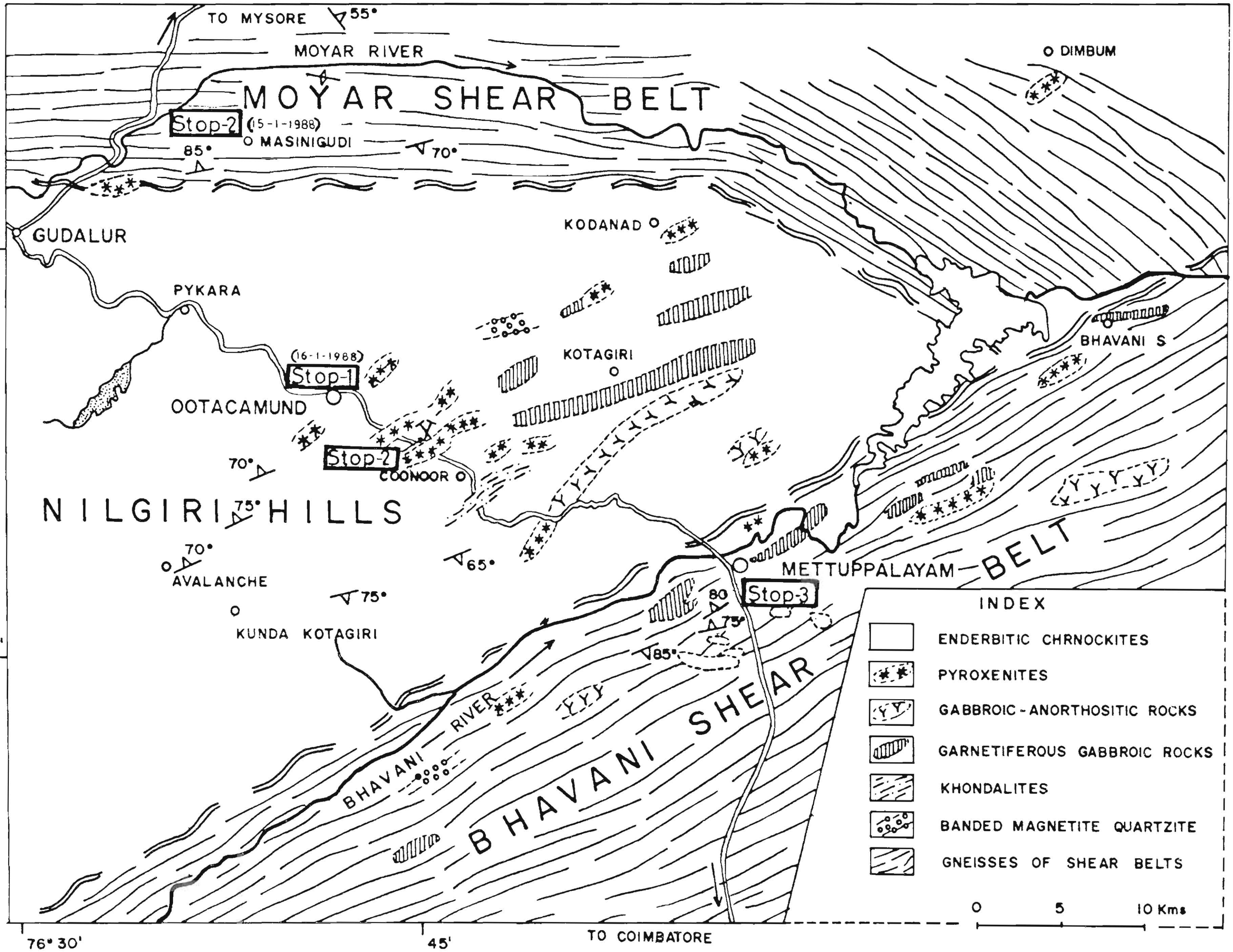


Fig. 13. GEOLOGICAL MAP OF NILGIRI HILLS (after Srikantappa et.al., 1986)

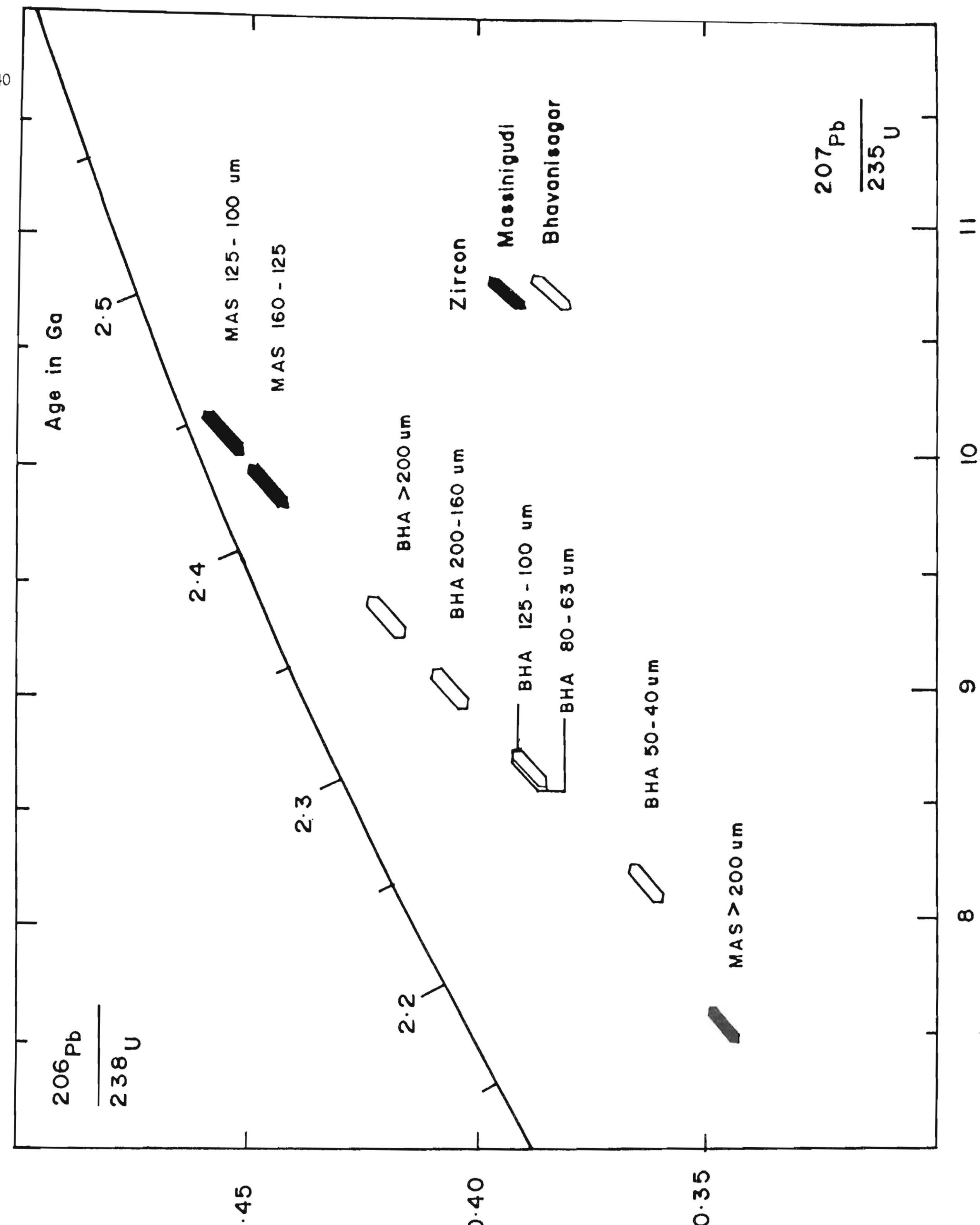


Fig.14 Concordia diagram for the U/Pb Zircon ages for the chornockite from the Moyar and Bhavani shear zone (after Buhl 1987).

Concordia diagram for the zircon from charnockites of the Moyar shear zone from this quarry gives an age of 2480 m.y.

Day 8

January 16, 1988

Guide: C. Srikantappa

Time		
0830		Leave Ooty and reach Doddabetta
0900	Stop 1	Doddabetta quarry
0930		View from Doddabetta
1030		Drive to Aravankadu and reach Mettupalayam During this drive from the top of Nilgiri (2695 m) to the plains of Bhavani valley (400 m) participants will see some glorious hill sections, steep sided valleys which follow major shear zone.
1100	Stop 2	Aravankadu quarry
1200		Lunch break, Mettupalayam
1330	Stop 3	Gudiyur quarry
1430		Leave for Madukarai
1530	Stop 4	Madukarai carbonate rocks
1630		Leave for Ooty

Stop 1. Doddabetta quarry.

In this quarry,on the way to Doddabetta, medium to [illegible] grained, greasy grey coloured garnetiferous charnockites are exposed. They exhibit typical 'massive' nature characteristic of Nilgiri charnockites and enclose small enclaves of plagioclase+hornblende±garnet bearing mafic bodies. Charnockite exhibit foliation trending N 60°E and dips vertically.

Stop 2. Aravankadu quarry.

In this quarry garnetiferous charnockites predominate with foliation trending N 50°E and dips 85°SW. Tight isoclinal folds trending N 55°E, plunging 35°NE are noticed. Development of garnet appears to follow fold patterns. Pegmatitic coarsening is observed within charnockite. Numerous isolated but continuous bodies of pyroxenites occur (Fig.15). Individual enclaves vary in size from 1 m to a maximum of 2 to 3 metres in width and 2 to 4 metres in length. The enclaves are rounded to oval in shape, often showing stretching parallel to regional foliation. They generally show sharp contacts with the charnockites, occasionally with biotite rich selvedges. Pyroxenites show development of two sets of fractures trending N 40°W and N 35°E. Relict foliation is observed in few enclaves. In intensely deformed zones, vein like invasion of quartzofeldspathic mobilizates into pyroxenites is observed. All these features suggest that the pyroxenitic bodies represent a separate suit of meta-igneous bodies, not genetically related to charnockite.

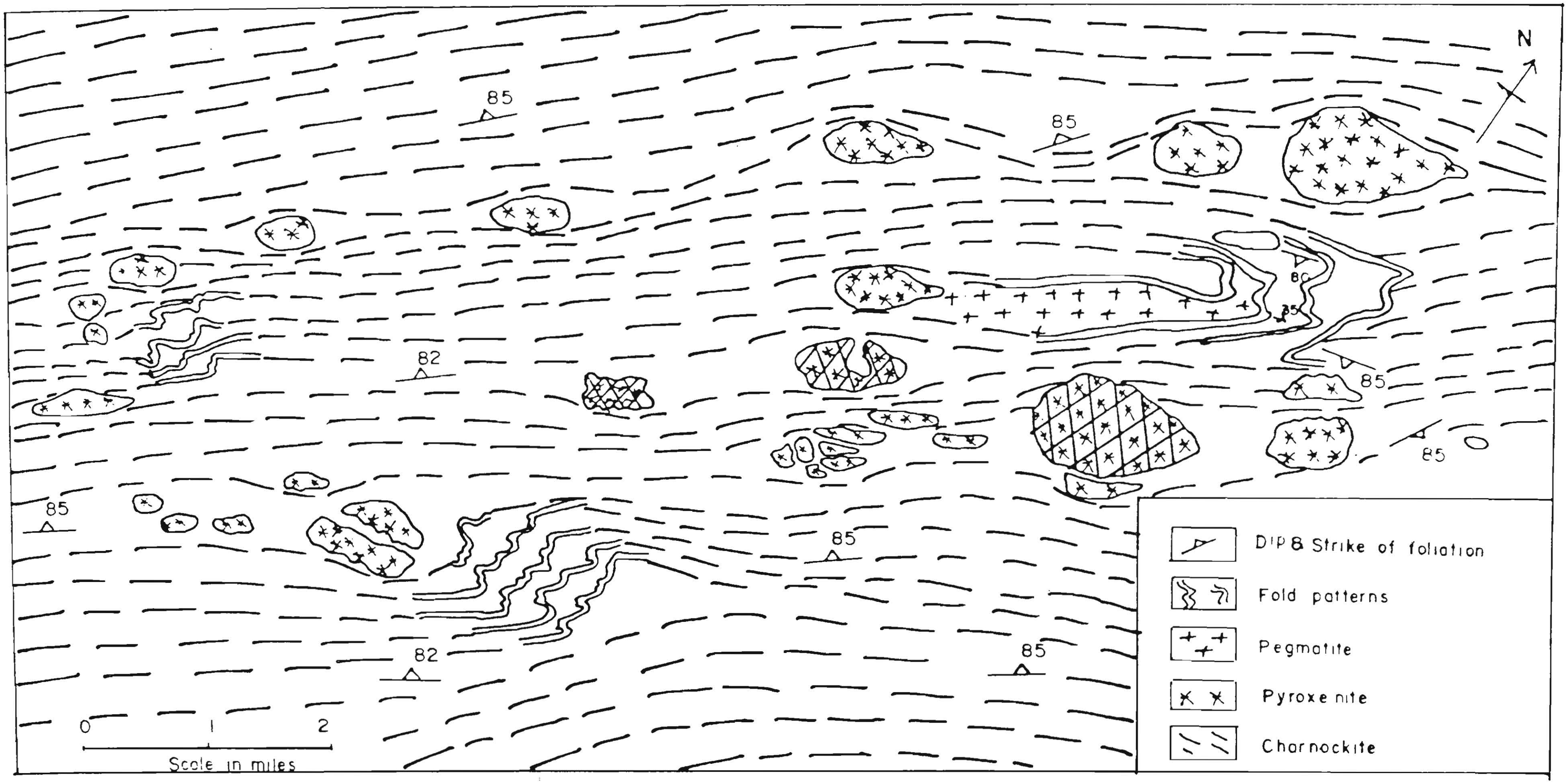


Figure 15. Sketch map of Aravankadu quarry (Ashamanjari)

These meta-igneous bodies have been rotated and sliced up during different stages of deformation.

Major and trace element data of these pyroxenitic bodies show chemical similarities with picritic basalts and do not exhibit komatitic chemistry (Srikantappa et. al, 1986). They also do not show any genetic relationship with ultramafic rock reported from Bhavani shear belt.

Stop 3. Gudiyar quarry.

This quarry exhibits various features related to retrogression of charnockites and is very much similar to the one the participants had seen near Masinigudi within the Moyar shear zone. The main things to notice in this quarry are the different stages of retrogression observed in charnockite. More than 80 per cent of the exposed area is represented by medium to coarse grained, grey biotite gneiss with relics of highly irregular, grey coloured non-garnetiferous charnockite patches.

Foliation in the gneiss trend N 70-80°E with lineation plunging 40-50°NE. Two sets of shear planes trending E-W and N 15°E occur sub-parallel to the general foliation. Intensity of shearing is variable along these shear planes resulting in the development of flaser and mylonitic textures. At the junction of two sets of shear planes as well as in intensely sheared areas, development of dark grey mylonitic patches are noticed. On close observation these dark grey patches represent fine-grained, highly irregular network of pseudotachylites. Thin section studies of these show fine-grained, equigranular texture with feldspar+quartz+ biotite. Presence of a melt phase is noticed.

Towards the northern part of this quarry, 2 to 5 metre wide, melanocratic dyke-like bodies of pseudotachylite are exposed. These features which are quite common adjacent to Nilgiri charnockite massif is taken as evidence for the block uplifment of Nilgiri charnockite massif (Narayanaswami, 1975).

Standing at this quarry the participants can see the magnificent wall of the Nilgiri hills. Looking the south, they can see small hill ranges predominantly consisting of mafic bodies forming part of the Bhavani layered complex.

Stop 4. Madukkarai (Coimbatore).

The Precambrian 'terrain around Madukkarai' (9 km south of Coimbatore city) is essentially a charnockite terrain. The charnockite and its retrogressed product banded gneisses contain huge metasedimentary enclaves. The metasediments consist of dominant carbonates, pelites (garnet-biotite-sillimanite-graphite-bearing gneisses and sparse BIF (Fig.16). These are grouped under the name Khondalites by Tamil Nadu geologists. In the vicinity of Madukkarai, the carbonates and the pelites occur as jagged hillocks, amidst a plain country made up of charnockites. Massive charnockites forming a part of the western ghats can be seen in the distance. The carbonate bands can be discontinuously traced westward to 20 km. The above sequence of metasediments, gneisses and

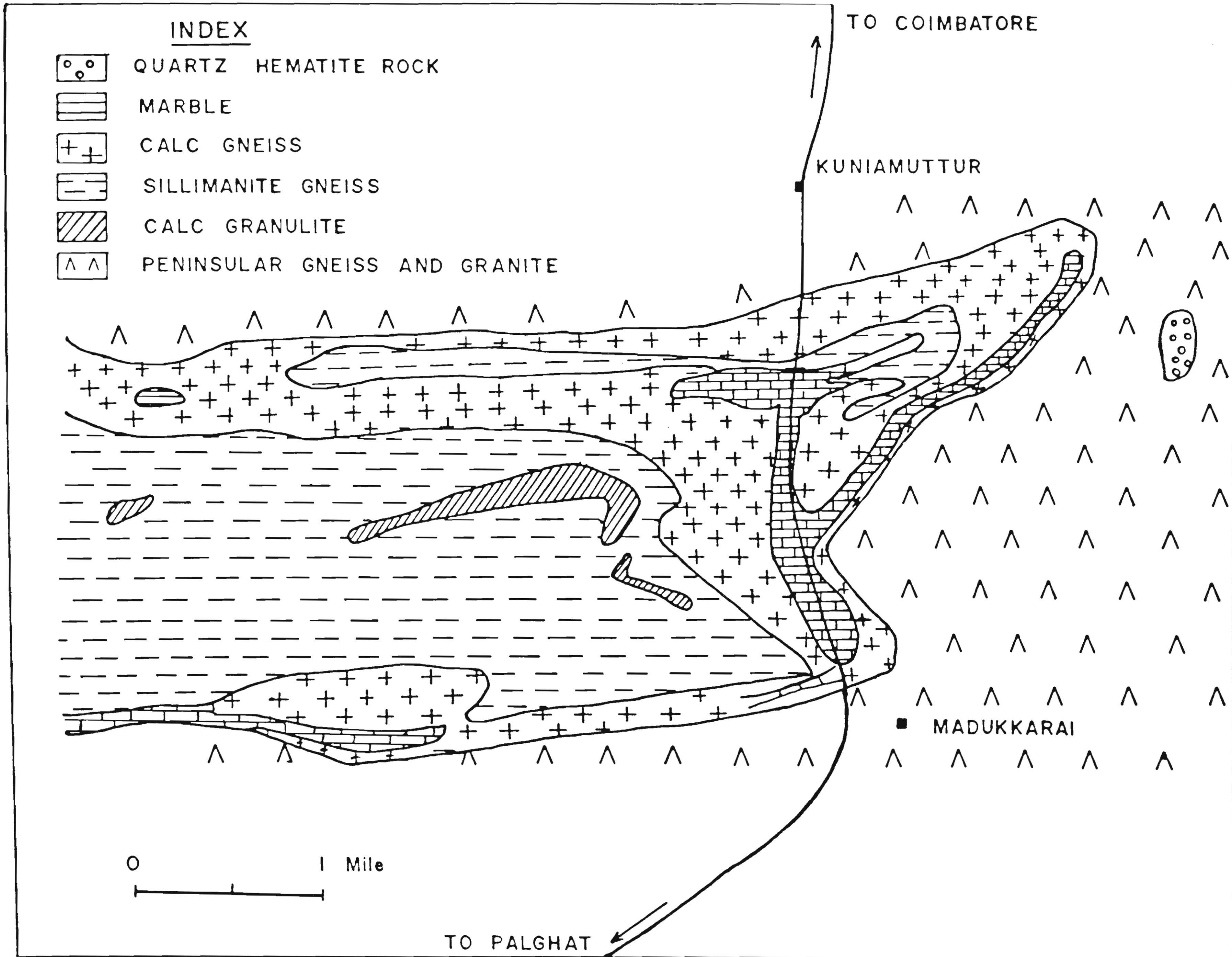


Figure 16. Geological map, Madukkarai (N.L.Reddy,1975)

charnockites are intruded by granites (Reddy, 1964). Carbonates of Madukkarai occur in such abundance that they are able to sustain a medium sized cement factory.

Carbonate of Madukkarai can be divided into three varieties - calc-granulites, marble and calc-gneisses. Calc-granulite rocks consist of pale green diopside (slightly aluminous to be termed as aluminous diopside) bluish green hornblende, calcic plagioclase, grosgular garnet, sphene, graphite, calcite. Wollastonite presence is significant. According to Reddy (1964) Wollastonite and grossular garnet exhibit an imcompatible relationship. Microcline and quartz are the other minerals introduced during migmatisation. Pressures of 6.5 Kb have been obtained from sillimanite-garnet-plagioclase quartz barometry.

ODDANCHATRAM ANORTHOSITE

Day 9

January 17, 1988

Time	
0800	Leave Ooty
1030	Coimbatore
1300	Oddanchatram via Palni
	Lunch break
	Examination of anorthosite of Oddanchatram - K.N.Malai
1500	Leave for Madurai
1800	Madurai

Anorthosite of Oddanchatram.

The Oddanchatram anorthosite is one of southern most bodies in a suite of Proterozoic anorthosite plutons that lies within a broad zone trending along the southeast coast of India. Although most of the bodies like Chilka lake, Nellore lie within the Eastern Ghats Mobile Belt (Middle Proterozoic) this body and the Kadavur body (Subramaniam,1956) lie outside to the SW of this belt. All these bodies exhibit structures and textures suggesting deformation and metamorphism, subsequent to their emplacement (De, 1969). Recently, it has been demonstrated that Oddanchatram body has also developed locally, particularly along its margins, mineral assemblages that suggest post emplacement deformation and metamorphism (Janardhan and Wiebe, 1985). In this aspect, all these bodies have similar histories to the deformed and metamorphosed anorthosites of the Grenville belt of North America (Ashwal and Wooden, 1985).

Geological setting.

The Oddanchatram anorthosite (Narasimha Rao, 1964; 1974) is located in the Madurai district of Tamil Nadu, 17-20 kms. east of the pilgrim town Palni. The anorthosite body is almost lenticular shaped, 60 km at its longest by 15 km at its broadest. Good exposures of this body, are seen towards the southern margins of this body, as low hummocks (cf. Virupakshi, K.V.Malai, Oddanchatram). Oddanchatram and the Kadavur bodies (Subramaniam, 1956) occur along the same N 60°E line, along the northern slopes of Kodaikanal hill ranges.

A sketch map of the Oddanchatram body is appended (Fig.17). The outline of the intrusion is after the map of Narasimha Rao (1964). This small pluton occurs within the extensive granulite facies terrain of south India. The terrain consists locally of basic two pyroxene granulites, charnockites and metasedimentary rocks like quartzites, pelites and calc-silicates. The body itself describes a low elliptical area, surrounded by resistant rocks, quartzites and country rock gneisses.

The age of the body is inferred to be Proterozoic, as it intrudes a dominantly charnockite terrain of 2600 Ma. Further the body has all the characters of Proterozoic massifs, in that it is a largely massive, coarse grained pluton, containing on average 90% plagioclase feldspar modally, which often show blue iridescence and generally has An_{50-60}.

Mafic lenses extremely rich in pyroxene and Fe-Ti oxides characteristic of Proterozoic anorthosite bodies are common to Kadavur (Subramaniam, 1956) and recently have been found in Oddanchatram body also (Janardhan and Wiebe, in prep.).

Plagioclase in the anorthosite displays abundant secondary twinning features and have strongly sutured borders, suggesting post emplacement deformation. The most common mafics within the anorthosite are hornblende, augite and sparse orthopyroxene. Pyroxenes generally occur as equant grains. Hornblende grains exhibit characters suggestive of post-emplacement growth. Garnet and symplectitic orthopyroxene and plagioclase (An_{90}) occur only as reaction products around assimilated country rocks, particularly well seen along the margins of the body, as at K.V.Malai (Stop 1).

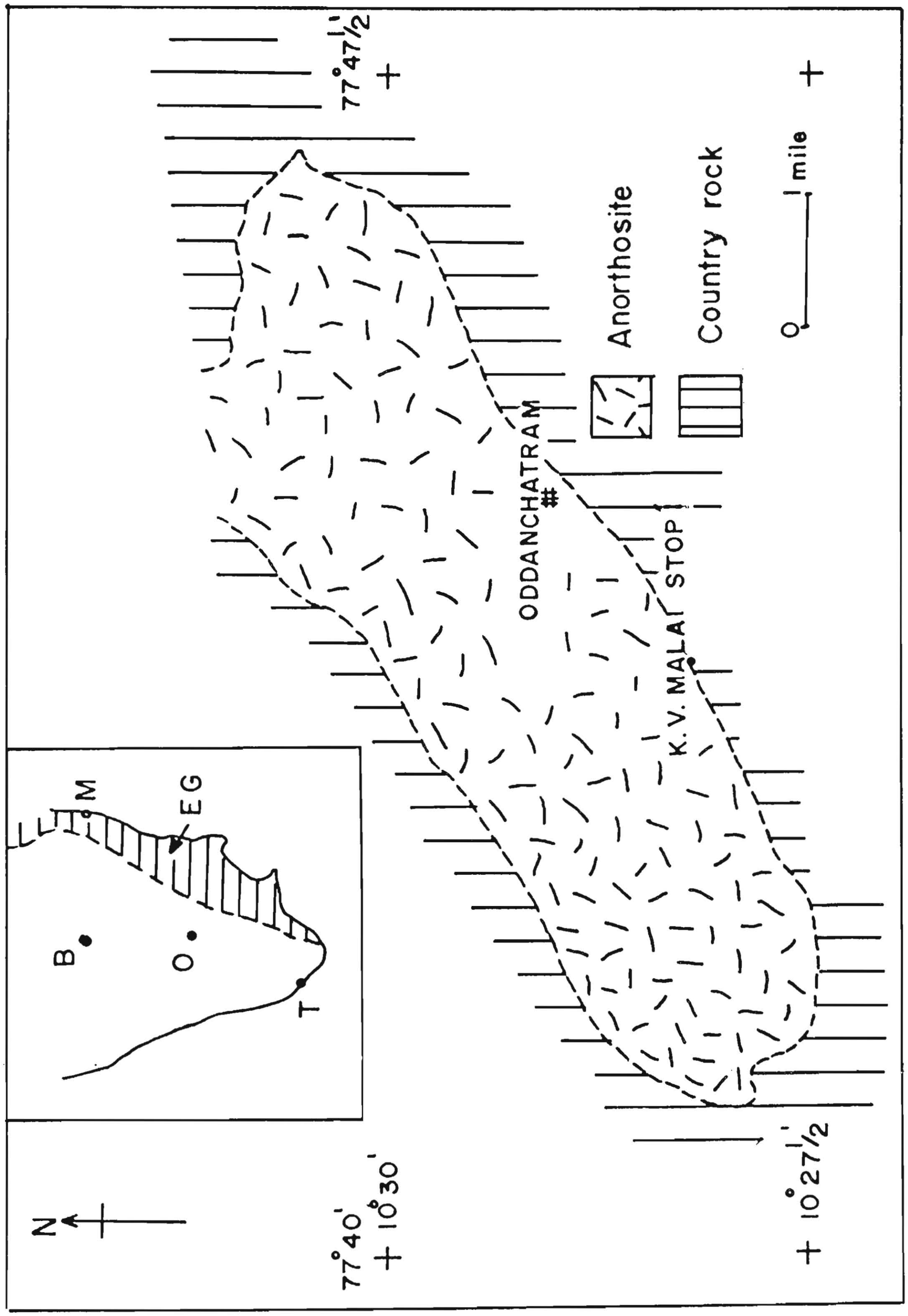


Figure 17. Oddanqhatram anorthosite body
(after Narasimha Rao,1964)

As stated earlier, contacts of the anorthosite with the surrounding rocks are well exposed. These areas contain abundant elongate inclusions of basic granulites, as can be seen at the southern margin of the Oddanchatram hillock and K.V.Malai (Stop 1) and lesser amounts of garnet-bearing quartzites, as can be seen at Virupakshi. At K.V.Malai (stop 1) large calc-silicate xenoliths can be seen. At the contacts of xenoliths, the plagioclase of the anorthosite is more calcic and porphyroblasts of corrundum with rims of green spinel can also be seen. At K.V.Malai and in the southern margins of the hillock near Oddanchatram, anorthosite contains abundant two pyroxene granulite inclusions. The two pyroxene granulite commonly have thin (1-2 cms) rims of garnet amphibolite, where they are in contact with the anorthosite. Metamorphic mineral assemblages within the anorthosite suggest maximum conditions of about 900°C and 11 Kb and minimum conditions of 700°C and 6 Kb.

MADURAI TO TRIVANDRUM VIA KANYAKUMARI

Day 10

January 18, 1988

Guide: A.S. Janardhan

Time		
0800		Visit to Madurai Temple
0900		Leave Madurai to Kanyakumari
1300		Lunch break, Tirunelveli
1500		Kanyakumari
	Stop	Kottaram - charnockite quarry
1600		Leave for Trivandrum
1800		Reach Trivandrum

 Kottaram (7 km north of Kanyakumari).

Seven kilometres north of Kanyakumari, within the Nagercoil charnockite massif is a chain of quarries around Kottaram, exposing mainly medium to coarse grained massive charnockites with sporadic garnet. In the southern extremity of this quarried hill face is a vertical exposure of charnockite-khondalite intercalation. Here an approximately 3 m wide band of khondalite is interlayered with, and runs parallel to the foliation trend of the surrounding charnockite, with slightly diffuse boundaries. In addition to this persistent band, minor discontinous patches and veins of khondalitic assemblage also occur in the adjacent exposures.

The charnockite here is generally coarse grained with a mineral assemblage of orthopyroxene-plagioclase-K-feldspar-quartz-biotite-ilmenite-garnet. The khondalite band comprises sillimanite-garnet-spinel-plagioclase-K-feldspar-quartz-biotite. P-T calculations based on microprobe data on the various mineral phases in the two litho-types attribute $850 \pm 50°C$ and 6.5 ± 1Kbar for the charnockitic assemblage and $780 \pm 70°C$ and 5.5 ± 1.5 Kbar for the khondalitic assemblage (Santosh, unpublished data). Fluid inclusion studies indicate the presence of high density (0.80-0.97 g/cm^3) carbonic fluids in both the rock types. However, CO_2 inclusions are more abundant in the charnockitic quartz.

This is the only known locality from the Kerala region where a typical khondalitic rock with visible clusters of large sillimanite needles and spinel occur interlayered with a garnet-orthopyroxene charnockite and is hence considered important for studies related to mineral reactions and petrologic implications in admixed charnockite-khondalite lithologies.

KERALA KHONDALITE BELT

Guides: G.Ravindrakumar and M.Santosh

Day 12

January 20, 1988

Time		
0800		Start from Trivandrum
0820	Stop 1	Mannanthala study of gneiss-charnockite relation.
		Leave Mannanthala
0930	Stop 2	Kunnanpara study of gneiss-charnockite - mafic granulite - leptynite relation.
1030		Leave Kunnanpara for field stop 3
1100	Stop 3	Panayamuttom a khondalite quarry
1300		Leave for Ponmudi
1400	Stop 4	Ponmudi quarry gneiss charnockite prograde transformation
1500		Hike to Ponmudi hill top to study the structural relations between the partially charnockitised paragneiss unit and the khondalite - leptynite units.
		Overnight halt at Ponmudi hill resort in cottages.

Day 13

January 21, 1988

Time		
0800		Start from Ponmudi
0945	Stop 5	Kadamakod study of gneiss charnockite-leptynite relationship.
1100		Leave Kadamakod
1200		Reach Punalur and break for lunch
1245	Stop 6	Leave Punalur and reach Kadakaman study gneiss-charnockite-calc-granulite relationship.
1415		Leave Kadakaman
1500	Stop 7	Kottavattom study yet another prograde gneiss to charnockite relation.
1630	Stop 8	Leave Kottavattom for Trivandrum on the way back visit road-side quarries around Attingal.

FIELD TRAVERSES ACROSS THE KHONDALITE BELT

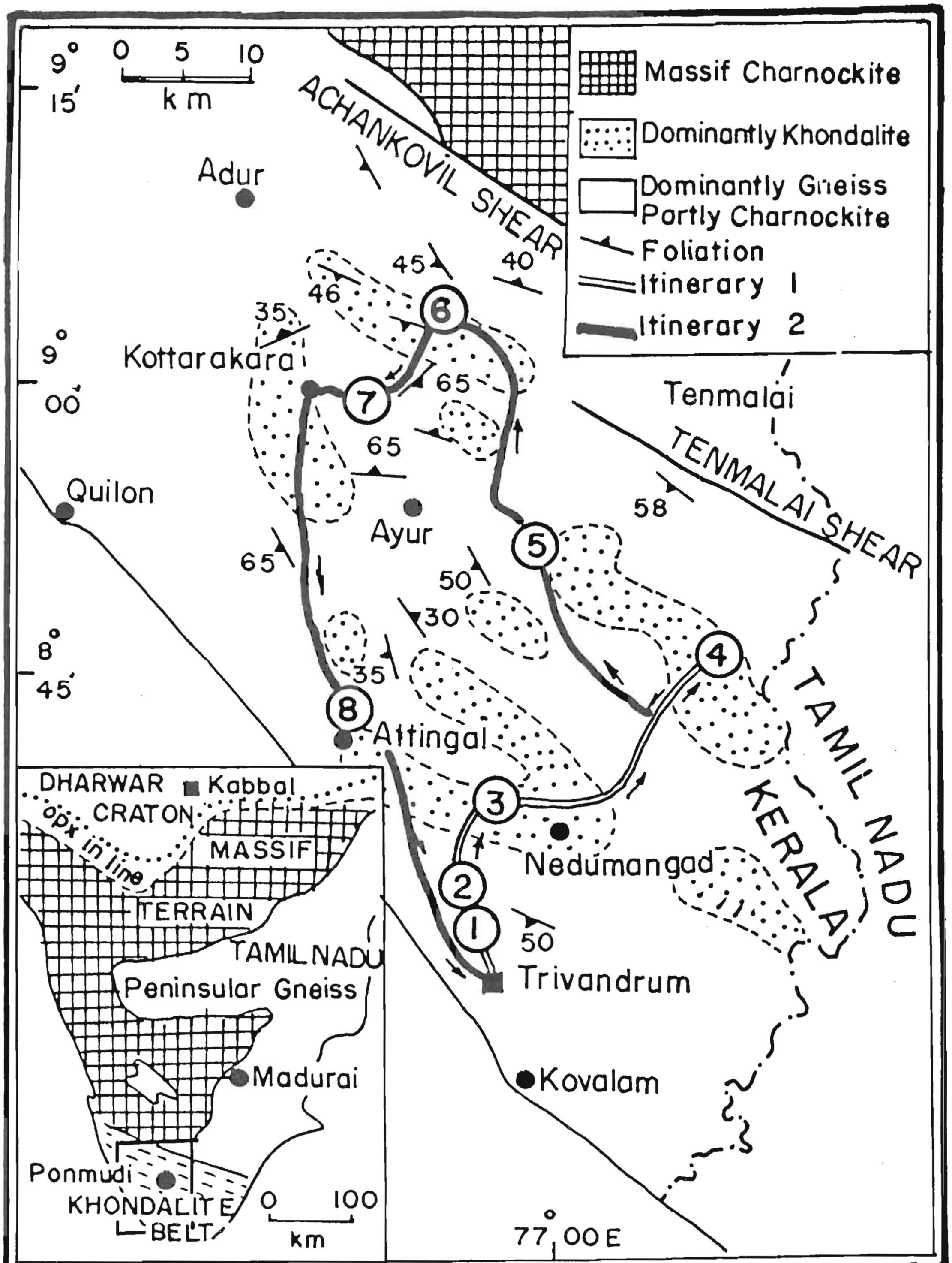
Field excursions of two days duration covering eight localities has been planned (Fig. 18). The traverse across the regional strike of the Kerala khondalite belt KKB is intended to give a broad spectrum of mechanisms of charnockite formation and breakdown in southern Kerala.

ITINERARY 1

This excursion takes traverse across the regional strike of the belt into the highlands of the ghats and focusses attention on aspects of charnockite in the making and charnockite in the breaking. Excellent cases of breaking of massive charnockite and two pyroxene granulites at Kunnanpara (N of Trivandrum) and late superimposition of charnockite in the making over garnet-biotite gneiss subsequent to retrogressive episodes, emphasizes the complexities in understanding the temporal differences in the making and breaking processes.

Stop 1 MANNANTHALA

This quarry is situated about 3 km north of Trivandrum. Garnet biotite gneiss is the dominant rock type. Coarse-grained, homogenous greasy green coloured patches of charnockite are noticed in conjugate orientation. The charnockite patches are irregular with no conspicuous foliation and vary in size from few centimeters across



1. Mananthala 2. Kunnanpara 3. Panayamuttom 4. Ponmudi
5. Kadamakod 6. Kadakaman 7. Kottavattom 8. Attingal

Figure 18. Geological sketch map of Kerala khondalite belt.

the width to few metres along length. Srikantappa et al (1985) and Yoshida and Santosh (1987) noted that the patchy charnockite development is a shear/fracture controlled phenomenon. The garnet-biotite gneiss is medium-grained and exhibits foliation by the alternate arrangement of garnet-biotite layers with quartz-feldspar layers. The charnockitised portion often cross cuts the gneissic foliation.

There is an intimate relation between the quartzo-feldspathic veins in the garnet biotite gneiss (late veins related to the migmatitic event) and patchy charnockite development. Yoshida and Santosh (1987) consider the quartzo-feldspathic veins as being emplaced during quasi dutile deformation of the gneiss. The occurrence of patchy charnockite only along the quartzo-feldspathic veins and their intimate relationship probably suggests the role played by these veins as conduits for the charnockitising fluids.

Chemical composition of gneiss and charnockite of Mannanthala area taken from Srikantappa et al (1985) is given in Table 10, page 77.

/Stop 2/ KUNNANPARA

This is one of the two best localities (other being Malayankil) to study different stages in the charnockite 'breaking' process. Kunnampara quarry is located about 5 km north of Trivandrum city. A mixed sequence of charnockite, mafic granulite, garnet-biotite gneisses, khondalite and leptynite are seen here. Charnockite

PLATE II

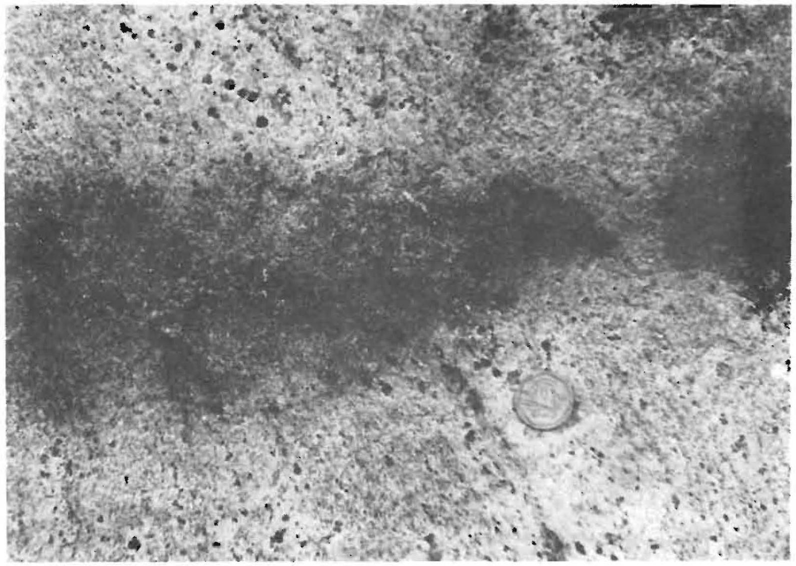
Figure Captions

Figure 2. Characteristic field appearance of incipient charnockites. Note the coarse grained nature of the charnockite patches (brown) and its cross cutting relation with garnet-biotite gneissic foliation.

Figure 3. Leucocratic quartzo-feldspathic gneisses (leptynite) with thin septa of khondalite (gar-bio-silli-gra $\pm$ cord) engulfing the mafic granulites as seen at Malayinkil. Closer look reveals a gar-bio rich retrogressive rim at granulite and gneiss contact. Similar features are also common in Kunnapara field stop 2.

Figure 4. A closer view of gneiss charnockite relation as seen near Ponmudi coarser grain nature of charnockites, disruption of foliation are notable with charnockite development.

Figure 6. Shear related charnockitization of well handed garnet biotite gneiss and leptynite layers at Kadamakod. The coarse garnets on tracing into the charnockitised patches show thin rim of opx away from charnockite contact to thick rims of orthopyroxene near to charnockite.



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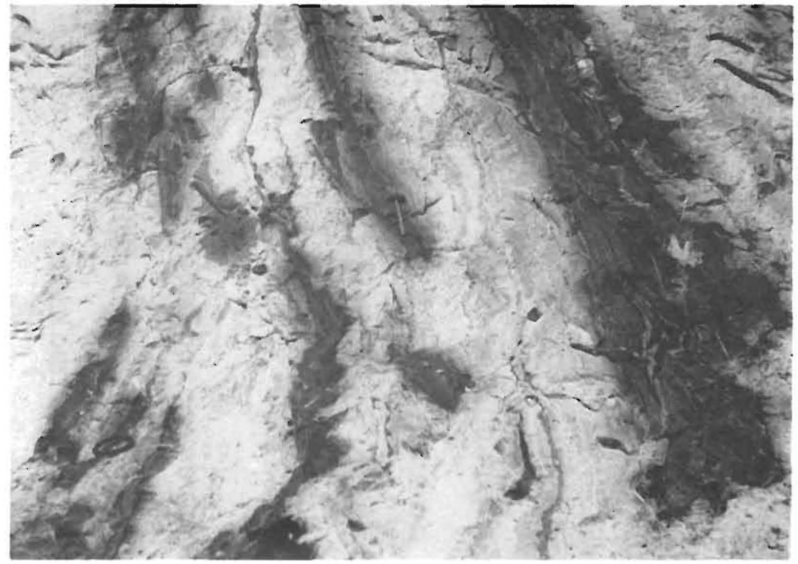

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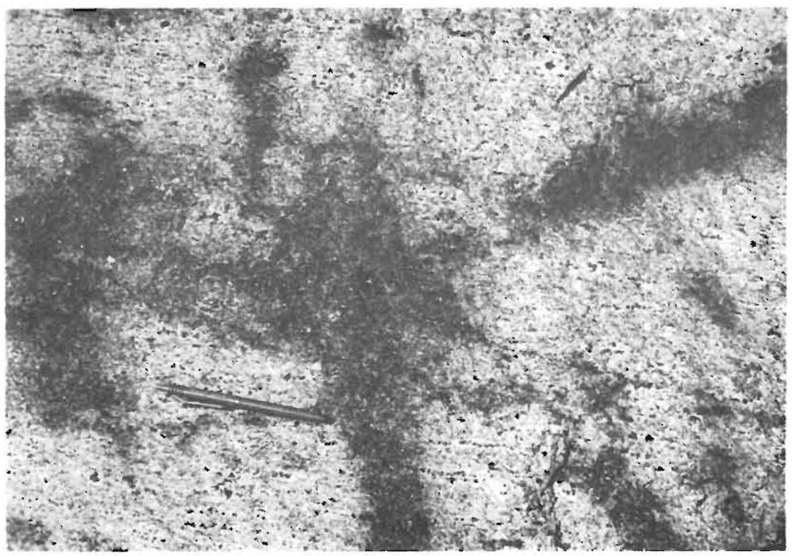

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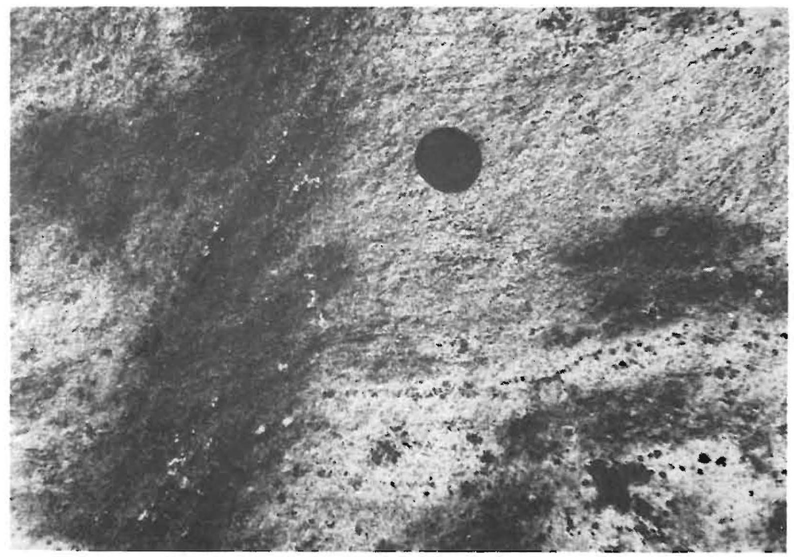

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PLATE II

(Plate-II)

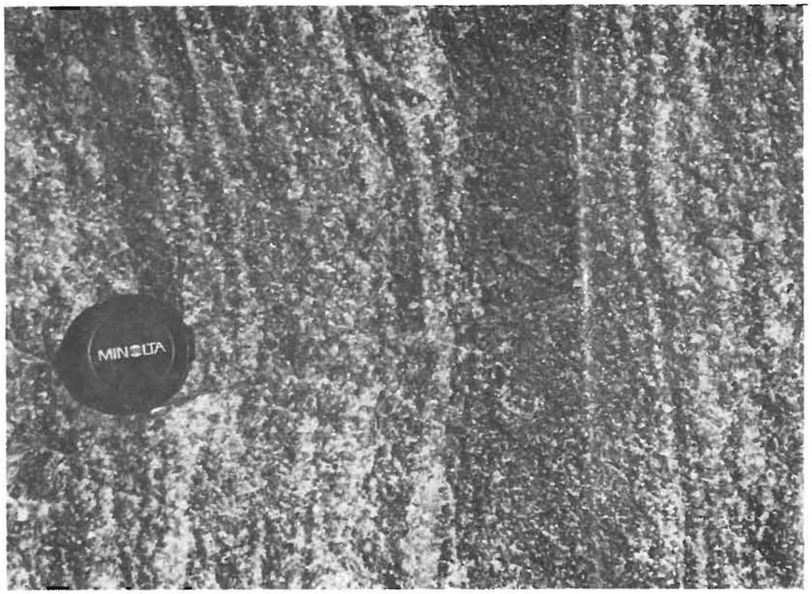
Figure Captions

Figure 7. Well layered calo-silicate (fine grained portion) and cordierite bearing charnockite association at Kadakamon.

Figure 8. Close up view of gneiss-charnockite relation at Kottavattom showing the coarser grain nature of charnockite and disruption of foliation about charnockite.

Figure 9. Characteristic field features associated with charnockites in the making. Observe warping and doming of patches about charnockite.

Figure 10. Pegmatitic dyke with a margin of coarse grained charnockite seen near village Kalanjur. This is yet another, not very uncommon type of charnockite in the making ascribed to decompression reaction of Na-Plag + gar + qtz = Ca-Plag + Opx.



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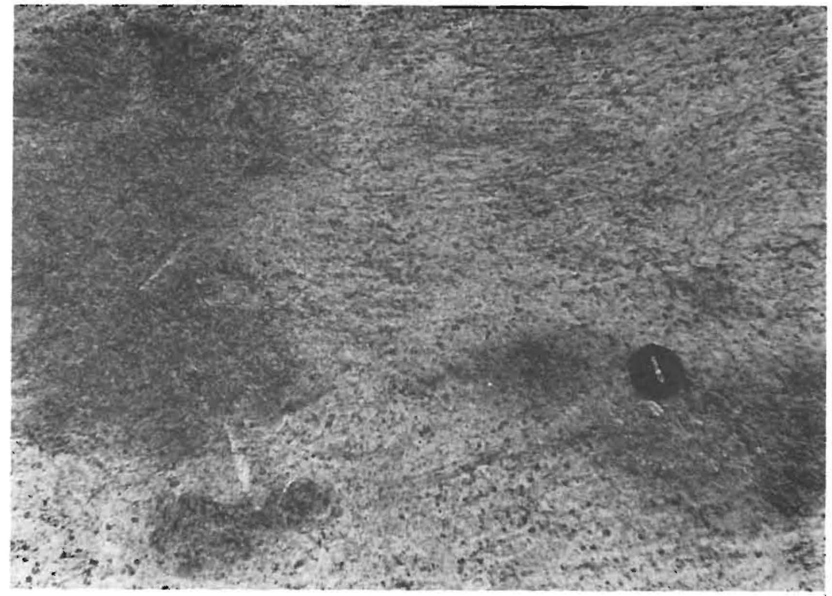

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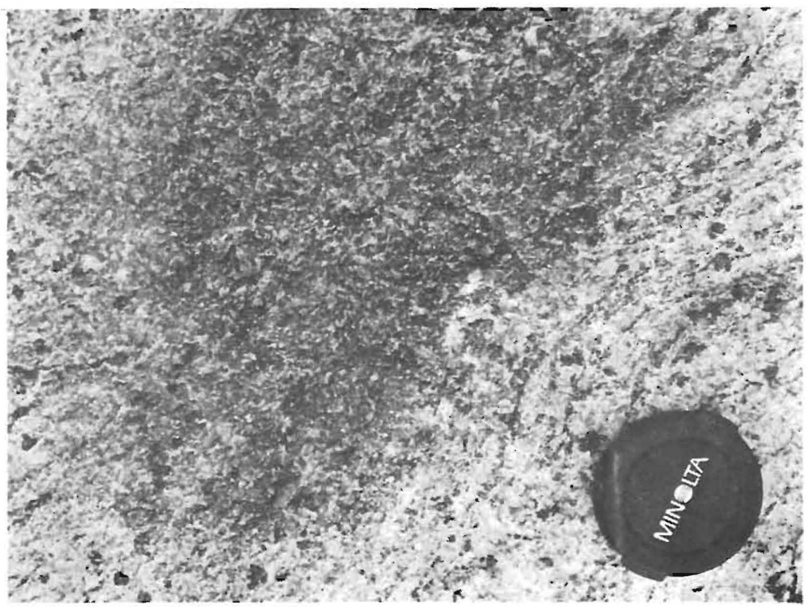

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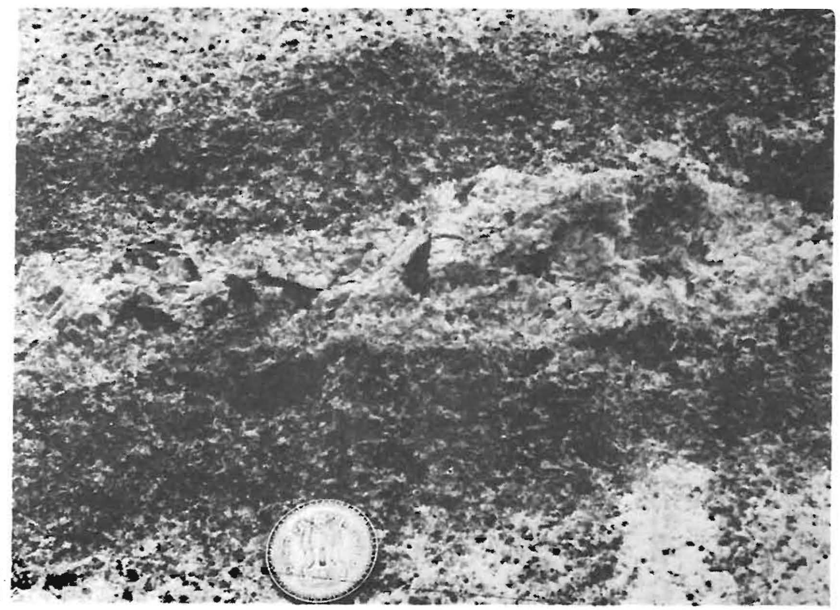

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PLATE II (continued)

is restricted to felsic zones and margins of the mafic granulites. Charnockite is made up of quartz + K-feldspar + plagioclase + hypersthene + garnet. The thick bands of mafic granulites are engulfed in leucocratic portions as cut, broken rotated and boudinaged patches (Plate II Fig.2). Their orientation is concordant with the general strike (N 20°W) of the associated rock types. Plagioclase, clinopyroxene, orthopyroxene and little biotite constitute the essential mineral constituents of mafic granulites. Medium to coarse-grained quartzo-feldspathic veins with orthopyroxene, occur as gradational layers sometime along the margins and many times as brownish acid charnockite patches within the mafic bands. Few examples of cross cutting relation between mafic bands and acid charnockite layers may be found in the quarry. Tight to isoclinal foldings are exhibited by mafic bands. Several cms to few metres thick palaeosome layers of khondalite (+sillimanite +cordierite) are also present in the interlayered sequence. They are highly migmatised and deformed. Sillimanite and graphite are conspicuous. The quartzo feldspathic gneiss which has mobilised all the early rock types has large porphyroblasts of garnet measuring 3 cm to 6 cm across. Biotite is scarce. The coarse grained nature and absence of foliation gives a pegmatitic look to the rock.

Yoshida and Santosh (1987) have documented by meso and microscopic studies the breaking down of mafic granulite into garnet-biotite gneiss and finally to garnetiferous gneiss.

/Stop 3/ PANAYAMUTTOM

This quarry is chosen to show typical field features associated with khondalite in southern Kerala. The quarry is located about 30 km north of Trivandrum. Alternating layers of khondalite and garnet-biotite gneiss are the major rock types seen. Khondalites essentially have garnet + plagioclase + K-feldspar + sillimanite + biotite + graphite. Pinitised cordierite occurs in many places of khondalite layers. Garnet-biotite gneiss is similar in appearance, without patchy charnockite, to the gneissic types seen in location 1 (Mannanthala). Gneiss and khondalites are traversed by quartzo-feldspathic gneisses which have coarse spotted garnets (1 to 5 cm in width).

Chemical composition of a typical khondalite from south Kerala is given in Table 10, **page 77**.

/Stop 4/ PONMUDI

This is one of the best localities to observe charnockite in the making and the first to be described from the khondalite belt. The quarry is located at Ponmudi hill resort which is situated about 60 km NE of Trivandrum. The proportion of gneiss to charnockite in the quarry is roughly 60:40. The gneiss is medium to coarse-grained with a composition of garnet, biotite, feldspar, quartz and graphite. Flakes of biotite and anhedral garnet define mineral foliation trending N 70°W. Thin leucocratic quartz and plagioclase bearing veins in these rocks is related

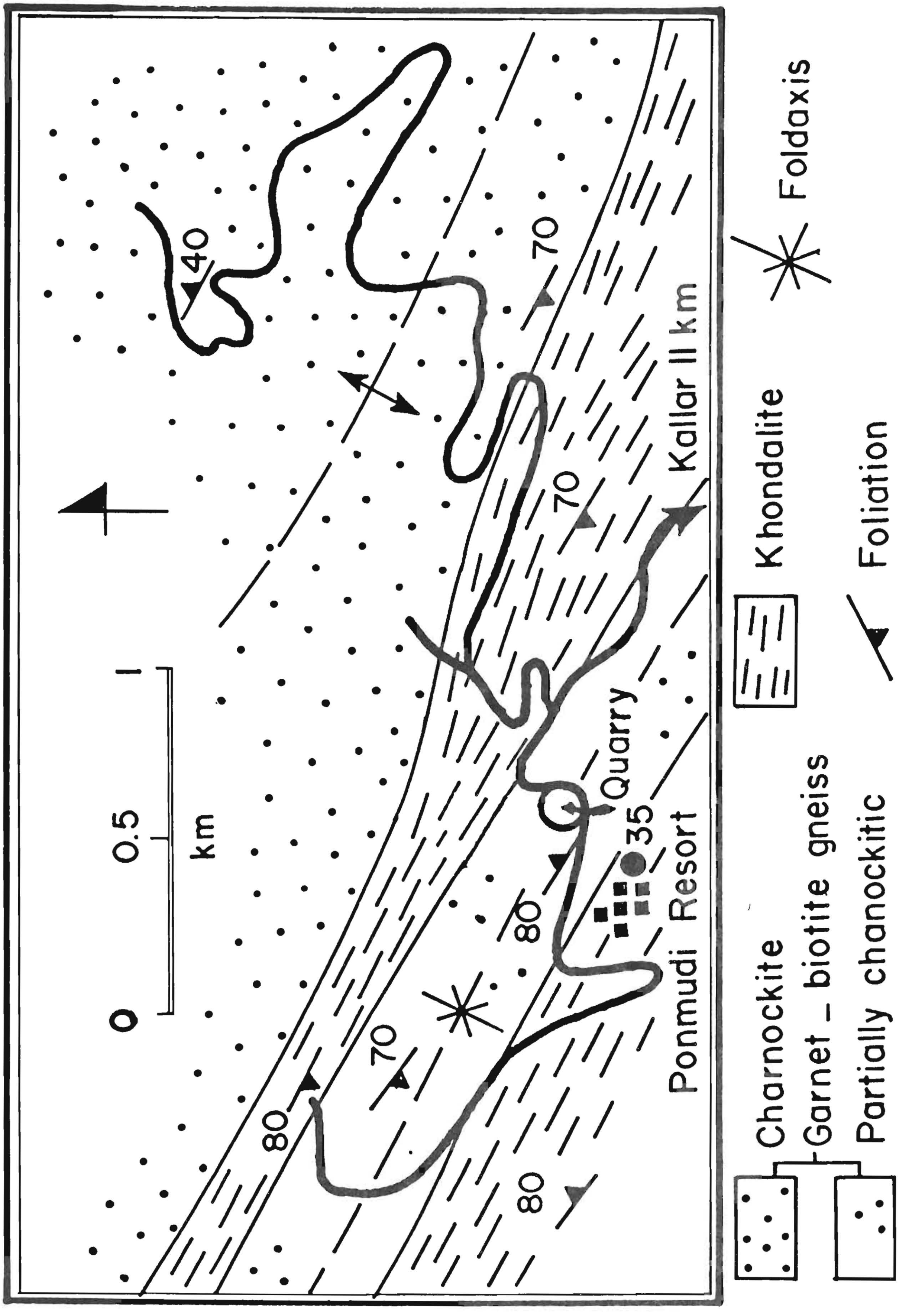

Figure 19. Geological sketch map of Ponmudi.

to migmatisation preceding the charnockite forming event. In the gneisses, numerous coarse-grained patches of greenish brown charnockites are seen obliterating the gneissic foliation to a variable degree (Fig.3). Closer examination of gneiss and charnockite reveal a drastic reduction of biotite from gneiss to charnockite. Thus, the basic orthopyroxene producing reaction appears to be bio + gar + qtz = opx + K-spar + V.

Preliminary structural work around the quarry reveals thatthe gneiss-charnockite is a discreet stratum occupying the core of a syncline (Fig.19). Many incomplete gneiss to charnockite transitions noticed in the vicinity of Ponmudi may probably belong to the same stratigraphic layer.

The close pair chemical analyses (see table 10,page 77) of gneiss and charnockite indicate a near isochemical nature of conversion to charnockite. There is, however, decrease of Rb in charnockite. The Rb loss can easily be assigned to the loss of biotite in charnockite and the metamorphism can be considered as of a closed system.

The microthermometric studies have revealed dense CO_2 rich fluid inclusions in both charnockite and gneiss (Ravindra Kumar et al 1985, Hansen et al 1987). They occur mostly in quartz as planar arrays. Some of the garnets also contain fluid inclusions which are generally of pseudosecondary nature. The freezing temperatures vary from -57.1 to -58.8°C and the homogenization temperature range from +6 to +19°C with a maximum at 9°C. The implied density is 0.90 gm/cm3.

Trekking to Ponmudi Hill Top

After observing the Ponmudi quarry one can take the road leading to the top of the hillock to observe the khondalite and leptynite units and the general structural disposition of partially charnockitic gneiss, leptynites and khondalite.

JANUARY 21, 1988

ITINERARY 2

This traverse is almost a N-S central cross section of the south Kerala khondalite belt. The traverse also gives a glimpse of the Kerala environs and human habitation. This ideal cross section is planned to cover almost a full day, from morning 0800 a.m. to evening. About an hour is considered enough at each quarry. If time is available extra, few stops may be made on the return route at Kottarakkara and Attingal to observe few retrogressive charnockite-gneiss transitions.

/Stop 5/ KADAMAKOD

This is one of the many localities in south Kerala exhibiting incomplete conversion of garnet-biotite gneiss to charnockite. This locality is very similar as it falls in the NW strike continuation of Ponmudi and probably belongs to the same paragneiss sequence. Presence of leptynite with huge garnets and absence of graphite, make them, however, different from the exposures at Ponmudi.

The quartzo-feldspathic gneiss and gneiss are generally interlayered but in places gneiss transgress the gneissic foliation (Plate I Fig.5). The development of charnockite is dominantly parallel to foliation. However, in numerous places linear bands of charnockite along N70°E direction cut across both the gneissic foliation and the leuco gneiss (leptynite).

374 The development of charnockite is accompanied by the blurring and warping of gneissic foliation. Garnet bands traced into charnockite show rims of orthopyroxene implying migmatization preceded development of charnockite. This point is further strengthened by the warping of concordant leptynite bands around charnockite filled shears.

The chemical data available on four adjacent gneiss and charnockite pairs suggest isochemical metamorphism (see Table10) p.77 The mineral compositions of biotite is high in TiO_2 and F (Chacko et al 1986) and fluid inclusions are rare (Hansen et al 1987).

Stop 6 KADAKAMON

This is a unique and interesting locality among all the known exposed gneiss-charnockite mixed quarries. The quarry is situated 5 km north of the town Punalur. Here, charnockite is seen as an interlayered sequence with scapolite bearing calc-silicates. Vestiges of charnockitization process are noted.

The calc-silicate ranges in thickness from 1-10 cm thick bands to 60 cm blocks. The mineralogy of charnockite is orthopyroxene + biotite + quartz + garnet $\pm$ cordierite. Calc-sillicate is made up of scapolite + quartz + andradite + clinopyroxene + calcite. There are numerous quartz veins, ranging in thickness from 1 to 10 cm cutting across the gneissic foliation. Few quartz veins branch out from the main cross-cutting vein and extend parallel to foliation. Large orthopyroxene crystals are present both within and along the quartz vein. Coarse charnockites are noted at the terminal end of the quartz vein, obliterating the foliation of the gneisses, another clear instance of charnockite in the making.

Chemical data suggests that original rock types were an interlayered sequence of shale and limestone (see Part I, Table 10). Ravindra Kumar and Chacko (1986) consider this sequence as significant in illustrating the possible role of supracrustal carbonate rocks in the formation of granulite facies mineral assemblages. The carbon stable isotope data of Santosh et al (1987b) show δ C values of + 1.2‰ for calc-silicate and -10‰ for the charnockites. This data and the mineral assemblage scapolite (Me_{88}) + calcite in the calcareous rocks, suggest high P CO_2 condition (Aitken 1983), attesting to the role of (some amount of) extraneous carbonic fluids in the development of charnockite.

Stop 7 KOTTAVATTOM

This quarry is located near the village Kottavattom. The predominant rock type is a garnet biotite gneiss. Patchy growth of charnockite varying in size from 8 cm - 30 cm are noticed randomly all over the quarry. The gneiss to charnockite ratio is about 20:80. Srikantappa et al (1985) considered this locality as representing initial stage in the charnockitization processes. Closer examination indicates total obliteration and coarsening of grain size in the charnockitised patches. Warping and doming of foliation is very distinct (Figs. 7 & 8). Marked reduction of biotite in charnockite, and no obvious change of shape or ratio of garnet from gneiss to charnockite suggest that orthopyroxene has developed as a result of the breakdown of biotite in the presence of quartz.

/Stop 8/ ATTINGAL

Northeast of Attingal, a series of hillocks extend in a linear fashion along a northwest-southeast direction. They are seen for approximately 3 km. Several excellent working quarries are located on these hillocks. All of the quarries contain a varying mixture of garnet-biotite $\pm$ graphite gneiss and garnet-biotite $\pm$ graphite charnockite. Charnockite is coarse-grained than the gneiss. Gneissic foliation can, however, be traced right through the charnockitised portions. In a few of the quarries, K-feldspar-porphyroblastic garnet-biotite $\pm$ graphite bearing charnockite is seen. In all of the quarries, late pegmatite dykes cut across both gneissic and charnockite portions, developing gneissic margins. In places, a late generation of coarse-grained charnockite cuts across both the retrogressed gneiss and pegmatite, obliterating gneissic foliation. Some of the pegmatite dykes also develop hypersthene crystals and contain flakes of graphite. Few dykes with charnockite margins appear similar to one described at Kalanjur (see Fig.9) by Ravindra Kumar and Chacko (1986).

Although the complex relations noted in these quarries do not allow tracing of any clear cut sequence of events, field relationships suggest the possibility of two generations of charnockite. An early episode of charnockitisation partially or completely effecting transformation of gneiss to charnockite, and a late generation of charnockite through intrusion of pegmatites with variable fluid composition causing retrogression in places and charnockitisation in others. These two charnockite types may be different phases of one and the same major event or separated by considerable time hiatus.

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